A DISSERTATION FOR THE DEGREE OF MASTER OF SCIENCES

The Growth of Teak (*Tectona grandis* Linn.f) in Different Aged Plantations in Bago Yoma Range, Myanmar

미얀마 동부 및 서부 바고요마 지역의 임령이 다른 조림지에서 티크(*Tectona grandis* Linn.f) 생장에 관한연구

BY

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DEPARTMENT OF FOREST SCIENCES

GRADUATE SCHOOL

SEOUL NATIONAL UNIVERSITY

AUGUST 2012

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UNDER THE SUPERVISION OF ADVISOR
PROF. VICTOR K. TEPLYAKOV

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

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MAJOR IN FOREST ENVIRONMENTAL SCIENCE
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APPROVED AS A QUALIFIED DISSERTATION OF
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FOR THE DEGREE OF MASTER OF SCIENCES
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Thesis Title: The Growth of Teak (*Tectona grandis* Linn.f) in Different Aged Plantations in Bago Yoma Range, Myanmar

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ABSTRACT

Due to the shrinking of forestlands including the natural teak (*Tectona grandis* Linn.f) forests, teak plantations have been established with a view to enhancing the natural stock of teak without destroying the existing ecological characteristics in Myanmar. These commercial plantations are to be assessed and evaluated to understand their silvicultural performance including growth, production potential and social and environmental implications. This study was designed to provide growth patterns of commercial plantations in order to help foresters, forest managers and decision makers to review plantation forestry in Myanmar and make appropriate adjustments in management strategies.

This study was carried out in two places in Bago Yoma Range – Bago (East Bago Yoma) and Paukkaung (West Bago Yoma) to investigate the growth of teak plantations in order to provide information on establishment and management of commercial teak plantations. There were three aged classes of plantations in Bago and four aged classes in Paukkaung site. Data were collected from sample plots (1.0 ha) in each study sites and all trees in the sample plot were measured for height and diameter at breast height (DBH), and around 20 trees in each sample plot were randomly selected to measure tree-ring width by taking tree ring cores. In this study, it was found that the average DBH growth rate was 1.23 ($\pm$ 0.62) cm yr^{-1} in Bago site and 1.40 ($\pm$ 0.95) cm yr^{-1} in Paukkaung site, and mean annual increment (MAI) was 3.7 m^3 ha^{-1} yr^{-1} and 4.8 m^3 ha^{-1} yr^{-1}, respectively. In Bago site, the stand basal area were 5.31, 7.84 and 12.00 $m^2 ha^{-1}$ with 496, 523 and 280 stems (> 5.0 cm DBH) at 10, 15 and 20 years age classes, and 11.16, 9.54, 11.83 and 7.21 $m^2 ha^{-1}$ with 571, 505, 307 and 136 stems (> 5.0 cm DBH) at 10, 15, 20 and 25 years age classes in Paukkaung site, respectively. The most suitable site-specific equations for the growth performance were found as the quadratic fit functions with the stand age (A): DBH = 9.595 -0.042 (A) + 0.048 (A^2) , Height = 1.951 + 0.942 (A) – 0.012 (A^2), Basal area = 0.020 – 0.002 (A) + 0.001 (A^2) and Volume = 0.076 – 0.015 (A) + 0.001 (A^2) for Bago site plantations, and DBH = 17.049 – 1.063 (A) + 0.057 (A^2), Height = 22.528 – 1.608 (A) + 0.060(A^2), Basal area = 0.035 – 0.003 (A) + 0.001(A^2) and Volume = 0.521 – 0.070(A) + 0.003(A^2) for Paukkaung site plantations. However, it was found that Michailoff (1943) function ($y = 1.3+a*exp^{(b/x)}$) for diameter-height relation curve and Richards (1981) function ($y = a/ (1+ exp^{(b-c*x)})^{1/d}$) for growth analysis could be used to investigate growth and yield tables for both study sites if data collection was continuous time series measurement and more observations. This study concludes that both study sites are suitable for the establishment of teak plantations considering ecological conditions: weather, soil properties and topography. Moreover, growth parameters of two study sites indicate that Paukkaung when compared with Bago site has better performance in growth in terms of diameter, basal area and volume, except height (same site index 40).

Keywords: stand density, tree-ring analysis, diameter-height relationship, growth and yield table, sustainable forest management.

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I. INTRODUCTION

1.1 Background

Teak (*Tectona grandis* Linn.f), is a species of worldwide reputation as paragon among timber trees, belongs to the family Lamiaceae and is distributed predominantly in tropical and subtropical regions. It is indigenous to only four countries in South and South-East Asia. Nowadays, dense natural forests with big and beautiful admiralty quality teak have been degraded and shrunk so rapidly that at present they are confined only to Myanmar and to some extent to India (Gyi and Tint, 1998).

Teak is one of the most important hardwood valuable species that is being planted extensively in several countries in the Asia-Pacific region. Being indigenous to the region, substantial experience has been gained in the management of natural and man-made stands of teak. The reasons for the relatively wide use of teak, where quality hardwoods are planted, are its ease of propagation, establishment and management, as well as its excellent wood quality. It is also one of the most valuable multi-purpose timbers of the world (Gyi, 1972).

Even though teak once covered a large percentage of India, Thailand and Myanmar and a small area of Laos, there is now very restricted distribution in each of these countries except Myanmar (Gyi, 1972). In Myanmar, natural teak forests have been managed for many years with sustained timber production as the primary objective. Myanmar is the only country producing large teak logs from natural forest, which attract a price advantage compared with small logs from plantations and which is likely to continue in the foreseeable future (Htun and Hlaing, 2001). However, the area and quality of teak forests are declining with the increasing population and greater pressure on forested land for conversion to agricultural land and illicit cutting. Forest resources, though scientifically managed since 1856, have been decreasing gradually both in extend and quality due to increased population pressure and consequent rising demands for timber for domestic and foreign uses. Annual production of teak is estimated to be about 450,000 m^3 in the period of 1991-2000 average which are decreased to 230,000 m^3 in 2000-2011 average, in the form of logs and sawn timbers, of which are mostly from natural forests (Kyaw, 2003a) (Figure 1). From forestry sector, the total foreign exchange earning of Myanmar comes from export of timber (Soe, 2009), about 90 % of which is derived from teak (Kyaw, 2003a). Although there were plenty of teak trees in the natural forests, in Myanmar, in various densities, teak plantations were established in a compensatory way up to 1962.

Myanmar is geographically situated in continental Southeast Asia, between 10˚ and 29˚ N latitude and 92˚ and 101˚ E longitude. With an area of 676,577 km^2, the country extends about 936 km from east to west and about 2,051 km from north to south. The population reached about 60 million in 2010 (ADB, 2011). Myanmar is essentially an agricultural country with about 70% of the population residing in rural areas. They practice subsistence agriculture and are dependent on forest resources for their basic needs and livelihoods. Forest covers about 33 million hectares constituting about 50% of the total area of the country. The forest cover consists mainly of natural forests, about 45% of which are teak bearing forests

(Kyaw, 2003a). Forest types vary widely across the country depending upon rainfall, temperature, topography and soil conditions. Myanmar's forests are of great economic value to the country. The economic importance of the forest resources has become so significant today that the revenue earned from forest resources is equal to those earned from the agricultural sector (Htun and Hlaing, 2001).

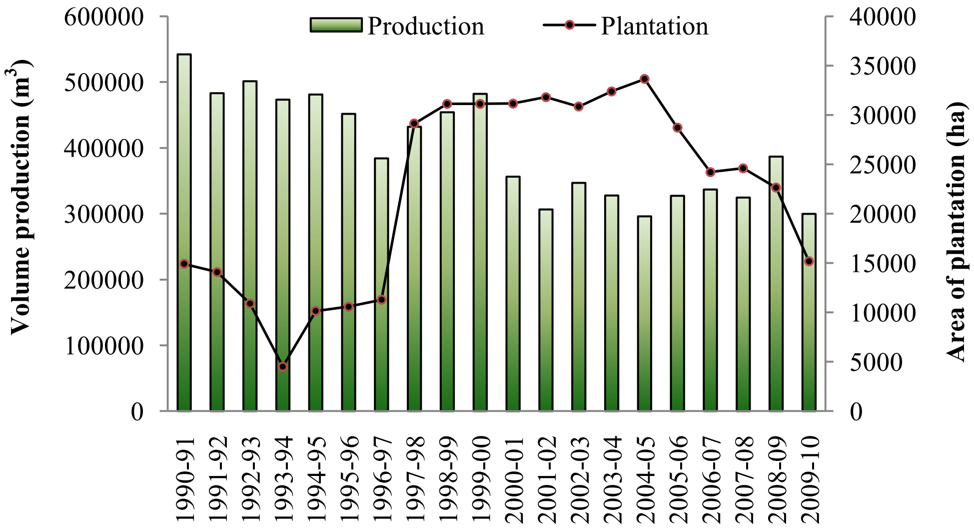


Figure 1. The annual production and plantation establishment of teak in Myanmar (FD, 2010 and Kyaw, 2003a)

In Myanmar, extensive teak plantations were established in the 1970s, and a further large-scale plantation program was launched commencing from 1980. The program started with an annual target of 6,200 ha, increasing gradually. The Forest Department (FD) of Myanmar launched a special teak plantation program in early 1998 in addition to the existing teak plantation scheme. The special program is incorporated with major reforms placing emphasis primarily on increased timber production and on overcoming the environmental constraints experienced by forest plantations. The special teak plantation program would, therefore, lead to the establishment of teak plantations over an area of 324,000 ha at the end of the 40-year rotation. A sustainable production of 572,000 m^3 to 930,000 m^3 of teak is estimated to be available annual from 8,100 ha of these plantations by the end of the rotation. Teak plantations will be formed only on locations with site quality II/III and better.

In Myanmar there are four broad ecological zones namely: Moist Humid (Northern Hilly Region), Dry Humid (Eastern High Plateau), Moist (Southern Plain, Hill and Deltaic Area), and Dry (Central Plain). Teak plantations are mainly concentrated in the Bago Yoma Region, which falls in moist ecological zones, a well known place of high quality natural teak forests. The area of teak plantations established in 1998 had already reached 195,043 ha, constituting about 41% of the total area of all plantations established in Myanmar. All teak plantations under different ecological zones are given in Table 1.

Table 1. Area and percentage of teak plantations by ecological zones (1982-1988)

Ecological Zone	Rainfall (mm)	Temperature (˚C)	Area (ha)	% of total area
Moist Humid	1540-4100	10-33	12,994	6.66
Dry Humid	1280-2560	10-33	3,363	1.72
Moist	2050-5130	18-37	129,403	66.35
Dry	770-1800	15-39	49,283	25.27
Total			**195,043**	**100.00**

Source: Htwe (2000)

1.2 The rationale of study

At present, the annual total plantation target for 1990-2010 has been fixed at around 361,807 ha of which commercial plantations constitute about 205,550 ha, representing 57 % of the total plantations (Soe, 2009 and FD, 2010). Amongst these commercial plantations, around 172,713 ha of teak plantations have been established and 51 % of these teak plantations are being constructed under Special Teak Plantation Program, which was commenced in early 1998 at Bago Yoma Range. This special program has a defined rotation age of 40 years and this program is, in fact, a national endeavor to maintain and increase the production of teak for both domestic and export markets with due consideration for social benefits and environmental restoration of degraded forests. With regards to establishing forest plantations, it is better noted that plantation forestry in Myanmar is not a substitute for natural forests management, supplementary as has been stipulated in the Myanmar Forest Policy, 1995 (Myint *et al*., 1999).

As discuss above, Myanmar has been establishing commercial plantations with major species such as teak for a long time. Forest Department did the assessment of commercial plantations in 1999 (Myint *et al*., 1999), so it passed one decade ago. Thus it is the time now that those commercial plantations are assessed and evaluated in order to understand their silvicultural performance including growth, production potential and social and environmental implications. It is therefore expected that this study will provide factual status of commercial plantations in the study sites to help foresters, forest manager and decision makers review plantations forestry in Myanmar and make appropriated adjustments in current management practices.

1.3 Objectives

- To investigate the growth of teak plantations for providing the information on establishment and management of commercial teak plantations

1.4 Research questions

- Does growth of teak plantations differ in two aspects (East and West) of Bago Yoma realm?
- How do the growth patterns of teak plantations related to rainfall and temperature?

1.5 Hypothesis

- H1: Teak plantations grow better in West Bago Yoma (Paukkaung study site) than in East Bago Yoma (Bago study site)
- H2: Growth pattern (tree-ring width) of teak tree is positively correlated with both rainfall and temperature

II. LITERATURE REVIEW

Tectona grandis is a large deciduous tree with a rounded crown and, under favorable conditions; it has a tall clean cylindrical bole of more than 25 m. The base of the tree is often buttressed (having outgrowths at the base caused by exaggerated root swelling) and sometimes fluted (having irregular involutions and swellings in the bole). Leaves are broadly elliptical or obviated and usually 30 to 60 cm long. Over most of its range, teak occurs in moist and dry deciduous forests below 1,000 m elevation and is one of the several species constituting mixed forest stands. It grows best in localities with annual rainfall of 1,250 to 3,750 mm, minimum temperature of 13º to 17ºC and maximum temperature of 39º to 43º C. Hotter and wetter weather is quite well also (Gyi, 1972).

The best teak forests, both natural and plantation forests grow in well-drained deep alluvium and a pH between 6.5 and 7.5. High calcium content has been found to be good. Teak plantations have failed completely when they have been established on low-lying, poorly drained land with clay soils (Seth and Yadav, 1958).

Teak is a light-demanding species and it does not tolerate shade or suppression at any stage of its life and requires unimpeded overhead light for its proper development. Teak coppices and pollards vigorously and sometimes retain its coppicing potential even after attaining large size. Teak begins flowering and seeding at a young age, about 20 years from seedling and about ten years from coppice, and produces abundant seeds almost every year (Seth and Khan, 1958).

The hard thick pericarp of the seed prevents easy germination and a considerable portion of fresh seeds remains dormant in the first year. Teak seeds remain viable for many years.

2.1 Ecology of Teak (*Tectona grandis* Linn.f)

2.1.1 Rainfall

Teak grows naturally over a wider range of climate conditions, from the dry (500 mm yr^{-1}) to the very moist (up to 5,000 mm yr^{-1}) (Seth and Khan, 1958; Kaosa-ard, 1981). Under dry conditions, the tree is usually stunted and shrubby. Under very moist conditions, the tree is large and fluted and usually behaves likes a semi-evergreen species; the wood quality is poor in term of color, texture and density. Teak grows best in a warm moist tropical climate within a rainfall range of 1,300 to 3,800 mm (Kermode, 1964; Gyi, 1972). However, the area where annual rainfall which between 1,200 mm and 2,500 mm with a market dry season of 3-5 months is the most suitable for growth and high quality production of the species (Kaosa-ard, 1981; Keogh, 1987). In Myanmar, teak of the best quality, production, producing cylindrical and sound logs, occurs in the Bago Yoma zone, where the annual rainfall ranges from 1,500 to 1,950 mm.

2.1.2 Temperature

Teak grows best when the minimum temperature of 13 to 17˚C and maximum temperature of 39 to 43˚C (Pandey and Brown, 2000). The species cannot stand forts, which often causes damage to seedlings and saplings (Kaosa-ard, 1981) and dieback (Gyi, 1972).

Teak seedlings grown in controlled environments demonstrated very poor development at 15˚C / 10˚C (day / night) but the species grew well in temperature of 21˚C/ 16˚C and higher. Within the temperature range studies, teak grew best between 27˚C / 22˚C and 36˚C / 31˚C. Performance at higher temperature regimes was not studied. The experiment also showed that the effect of night temperature on the development of teak was more pronounced than that of day temperature (Gyi, 1972).

2.1.3 Light

Teak is an obligate light-demanding species throughout its life cycle. Hence, it requires a high light intensity and the range 75-95 % of full daylight appears the most suitable for growth and development (White, 1991). However, Gyi (1972) found that the seedling development was affected very little by photoperiod in controlled environment studies except during extremely short days. Growth of the seedlings improved with increase in photoperiod from 8 to 12 hours per day but did not respond further with an increase from 12 to 16 hours per day.

2.1.4 Topography

The natural teak forests are mainly found below 1,000 m in elevation on hilly or undulating country. But it is also found on flat low-laying land (not swamps), which is subject to short periods of inundation during the rains. On well-drained deep alluvial soil teak sometimes occurs in remarkably pure stands, and it attains large dimensions. Growth is poorer on the upper slopes and ridges tops (Gyi, 1972). The species needs good sub-soil drainage for its best development; it does not grow well in a stiff soil liable to inundation.

Teak occurs on a wide variety of geological formations and rock types, such as limestone, granite gneiss schist, sandstone, conglomerate, shale and the igneous Deccan trap, the major Indian rock formation associated with teak (Kulkarni, 1951; Haig *et al*., 1958). However, the species does not grow well on soil overlying conglomerate, sandstone or laterite (Kadambi, 1957; Seth and Yadav, 1957; Takle and Mujumdar, 1957).

2.1.5 Soil

Teak can be found on a great variety of soil. The quality of growth, however, depends on the depth, drainage, moisture status and the fertility of the soil (Haig *et al*., 1958; Kermode, 1964; Gyi, 1972). Teak grows best on deep, well-drained alluvial soil. Conversely, the species performs very poorly, in terms of growth and stem form, on dry sandy soil, shallow soil, acidic soil (pH 6.0), and on compacted or waterlogged soil (Kulkani, 1951; Kaosa-ard, 1981; Bunyavejchewin, 1987). Soil pH is one of the limiting factors of the distribution and stand development of the species. Although the range of soil pH in teak forests is wide (5.0 - 8.0) (Kulkarni, 1951; Bunyavejchewin, 1983, 1987), the optimum pH range for better growth and quality is between 6.5 and 7.5 (Seth and Yadav, 1958; Kaosa-ard, 1981; Tewari, 1992).

Teak soil is ideally fertile with high calcium (Ca), phosphorus (P), potassium (K), nitrogen (N), and organic matter (OM) contents (Bhatia, 1954; Seth and Yadav, 1958; Sahunalu, 1970; Kaosa-ard, 1981; Bunyavejchewin, 1987). Several studies indicate that teak requires relatively large amounts of calcium for its growth and development, and teak has been named as a calcareous species (Seth and Yadav, 1958; Kaosa-ard, 1981; Tewari, 1992). The amount of calcium content in the soil is also used as an indicator of teak site quality. That is, the greater the proportion of teak to other associated species, the higher the calcium content in the forest soil (Bunyavejchewin, 1983, 1987).

2.1.6 Vegetation

Teak is found naturally in the tropical semi-evergreen forests, mixed deciduous forests and deciduous Dipterocarp or semi-Indaing forests. Teak usually occurs as scattered individuals or in small groups with little no regeneration presents (Kermode, 1964) in tropical semi-evergreen forest. Lower Mixed Deciduous forest (LMD) type of forest is found on low-lying alluvial soil through the teak bearing range. Teak may be found gregariously or in patches. The species attains a large girth and height and trees are greatly fluted in these forests. In Moist Upper Mixed Deciduous forest (MUMD), teak occurs more sparsely than in LMD but produces clear and straighter boles (Kermode, 1964). Dry Upper Mixed Deciduous forest (DUMD) type of forest produces teak of poorer quality than in the MUMD forests. Natural regeneration is frequent. In semi-Indaing (Deciduous Dipterocarp) forest, teak does not grow to a great size and usually are of poor quality. However, regeneration is often abundant and the species is found association with *Pentacme siamensis*, *Shorea obtuse* and *Dipterocarus tuberculatus* which may comprise as much as 80%, or more of the crop (Kermode, 1964).

2.2 Teak plantations in Tropical Asia

The earliest plantations of teak, apart from Java, has been traced back to 1680 when a Dutchman, Van Rhede (Perera, 1962), successfully introduced it to Sri Lanka. The first attempt at organized plantations in India was a teak plantation established in 1842 at Nilambur in Kerala, southern India, with the purpose of enriching the forests (Bapat and Phulari, 1995).

Natural teak forest in India covers about 8,900,000 ha (Tewari, 1992), but severe restrictions on the harvesting of teak from natural forests, introduced in 1997, have limited the domestic supply. The country has more than 500,000 ha of teak plantations, and there is a large ongoing program to plan almost 50,000 ha annually (Khullar, 1995). Since 1991, plantation companies in India have been promoting schemes offering investors teak trees at a nominal cost with an expectation of spectacular returns after as little as 20 years.

Teak is the most important timber species in northern Thailand, and as such, large areas of natural teak forests have been disturbed or become highly degraded. During the 1970s and 1980s, Thailand's forests were cut down to meet growing foreign demand for tropical hardwood and wood furniture; teak was especially prized. Between 1965 and 1989, Thailand forests and woodlands were reduced at an annual rate of 2.6 %, by 1989; leaving Thailand with 28 % forest coverage. Therefore, the Thailand government banned all logging of natural forest in 1989. In Thailand, the pioneer teak plantations were established from 1906, and teak plantations currently cover approximately on highly 159,000 ha (Krishnapillay, 2000). Thailand is now highly dependent on imports of plantation grown teak for its rapidly growing export-oriented furniture manufacturing industry.

Teak is also well established in Indonesia on the islands of Java and Muna where conditions are favorable for its growth. Almost 700 years ago Buddhist monks from Myanmar and Sri Lanka brought seeds or saplings over to Java. In the 19th century teak plantations were laid down in the East of Java, haphazardly at first, but soon a professional system was established. Even on the relatively small island of Java, wide differences in the quality of teak can be found because of varying rainfall and soil conditions. The area of teak plantation covers 1.081 million ha in which 0.837 million ha are suitable for the clear felling harvest system (Siswamartana, 1998). There are now many private owned teak plantations across Java.

The cultivation of teak is a relatively new undertaking in Malaysia. Most of the teak plantations (2,852 ha) can be found in the northern states of Peninsular Malaysia, especially in Kedah and Perlis. Perlis, being the northern-most states of Peninsula Malaysia bordering Thailand, has a similar climate to southern Thailand, i.e. with a distinct dry period of three months from December to February. However, teak plantations are also found in the state of Sabah (607 ha) and other states of Peninsular Malaysia (500 ha) that have been planted by private owners and villages. Most of teak seeds for these plantations were obtained from the teak seed production area located in the Forest Research Institute of Malaysia (FRIM) field station in state of Perlis and from the Forestry Department, Kedah.

Teak was introduced in Bangladesh from Myanmar during 1871 at Sitapahar Range, Chittagong Hill Tracts (Hossain, 2003). Initially, only few plantations were raised by direct sowing of seeds (Anon, 1959). From 1917 teak plantations started in an extensive scale, covering different part of Hill Tracts, Chittagong, Cox's Bazar and Sylhet forests. From 1934, stump planting was introduced with satisfactory results. Before 1975, teak was the main long rotation plantations species in Bangladesh, usually covering 60-70 % of annual planting area, because of its high value (Moef, 1993). Initially teak plantations were found promising in all the hill forest areas, but later on criticisms arose that it depletes soil fertility, prevents undergrowth vegetation and productivity depends on only suitable species site conditions. But the plantations appear likely to produce below the capacity of the site due to lack of proper maintenance.

In Nepal, government teak plantations began in 1960 in Chiliya, Rupandehi District (Kayastha, 1974) followed by some block plantations in Sagarnath, Sarlahi and Ratuwamai, Jhapa Districts by Forests Products Development Board, a few research plots at Sagarnath and other places were established by the Department of Forest Research and Survey. There is a lot of scope for promotion of teak plantations in suitable sites of Terai and Inner Teria of Nepal. Achieving shorter rotations of 20-30 years as applied in other countries is crucial for teak plantations in Nepal for both veneer and saw log production to get quick returns.

Elsewhere in Asia, teak is widely planted in Sri Lanka, China, Lao PDR, Philippines, Vietnam and Cambodia (Soe, 2009).

2.3 Teak plantations in Myanmar

Myanmar has a forest cover of about 33 million ha, which is almost half of its total land surface area in 1989 (Soe, 2009). The forest cover consists mainly of natural forests, about 45 % of which are teak bearing forests. The forest resources, thought scientifically managed since 1856, have been decreasing gradually both in extent and quality due to increased population pressure and consequent rising demands for timber for domestic and foreign uses. Annual production of teak is estimated to be about 450,000 m^3 (1991-2000 average) in the form of total foreign exchange earnings of Myanmar comes from export of timber, about 90% of which is derived from teak (Htun and Hlaing, 2001).

With a view to enriching the stocking in the natural teak bearing forests in Myanmar, teak plantations had been established in Paletwa area of the Chin State in about the year 1700 (FAO, 1956). The first attempt at teak plantations by Taungya method, which is world renowned today (Soe, 2009), was made in 1856 at Tharyawady in the Bago Division. However, plantations in those days were usually about 10 ha, with only one location exceeding 40 ha, and were established more with a view to increase the natural stock of teak rather than to create fully stocked stands. They were practiced to supplement or compensatory the natural regeneration of natural forest and, therefore, were called compensatory plantations (Gyi, 1972). In this compensatory plantation concept, silvicultural treatment, particularly thinning, was done up to age of 40 years and plantations, after heavy thinning at this age, were treated as natural forests and placed under the improvement felling schedules.

After the establishment of the plantations in Tharyawady forest division in 1856, plantation forestry continued and a total of 310 ha had been attained by 1867-68, and a relatively large area of 1,370 ha was reached by 1876. Between 1880 and 1900 the area planted annually increased from 400 ha to over 1,620 ha and there was a more definite effort at creating full stack even-aged stands. Teak plantations established up to 1906 totaled about 24,282 ha (Myint *et al*., 1999). The unsystematic ways in which plantations had been formed became the subject of considerable criticism and in response to the proposal by the Chief Conservator of Forests in 1906 the Government imposed limitations on the establishment of plantations in favor of improvement felling in the natural forests.

After the First World War in 1918, the Taungya system was firmly established and ever since, and it became the standard practice in Myanmar plantation forestry. By 1920, more than 32,376 ha had been established with teak. In 1937-38, the Government revised the policy to establish 600 ha of plantations annually. The total area of plantations by 1940 was 56,130 ha. No progress was made in plantations afterwards, but rather, many were destroyed during the Second World War. After the war, scattered plantations were made to enrich teak stocking in annual planting rates of no more than 20 ha. Plantation establishment was curtailed during the period of insurrection from 1948-62, but resumed in 1964. In those days it was adequate to rely on natural forest management with compensatory planting without taking risk for a new venture on large scale plantation forestry (Htun and Hlaing, 2001).

Starting from early 1970s, block plantations were formed in the areas with degraded forests and poor stocking of teak and other valuable commercial species (Gyi, 1972). As of 2000, 293,782 ha of teak plantations had been established which of 41% of total plantations. In early 1998, the Forest Department launched a special teak plantation program, which incorporates new features such as adoption of 40-year rotation, and management participation of interested and relevant communities. The adoption of a definite 40-year rotation reflects a significant deviation from the old concepts and final harvest will be made by clear cutting at the end of the rotation (Min and Lwin, 2004). The total teak plantations area is shown in Figure 2.

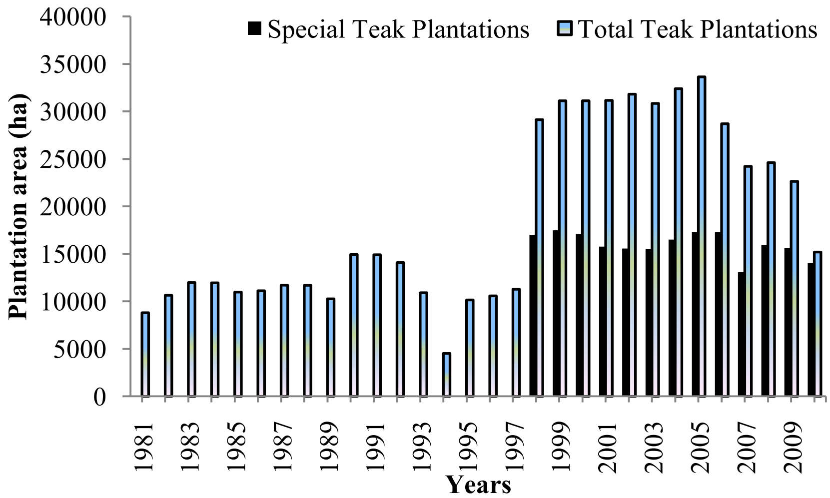


Figure 2. Establishment of Teak plantations in Myanmar (1981-2010)

(Source: FD, 2011)

2.4 Forest growth

Rate, as is true for size, is influenced by numerous variables such as soil, drainage, water, fertility, light, exposure. Basic to measuring trees and stands is an understanding of how individual trees develop in different situations. The relationships of tree size to age and increment to age are important to the forester particularly in predicting future growth (http://online.anu.edu.au).

Forest growth or forest growth models assist forest researchers and managers in many ways. Models provide an efficient way to prepare resource forecasts, but a more important role may be their ability to explore management options and silvicultural alternatives. Forest managers may require information on the present status of the resource (e.g. numbers of trees by species and sizes for selected strata), forecasts of the nature and timing of future harvests, and estimates of the maximum sustainable harvest. This information can be compiled from three sources (Vanclay, 1994):

1. area estimates of the existing forest,
2. stand level inventory of the present forest, and
3. growth and harvesting models based on dynamic inventory data.

Growth models may also have a broader role in forest management and in the formulation of forest policy. Used to advantage and in conjunction with other resource and environmental data, growth models can be used to make predictions, formulate prescriptions and guide forest policy (Figure 3).

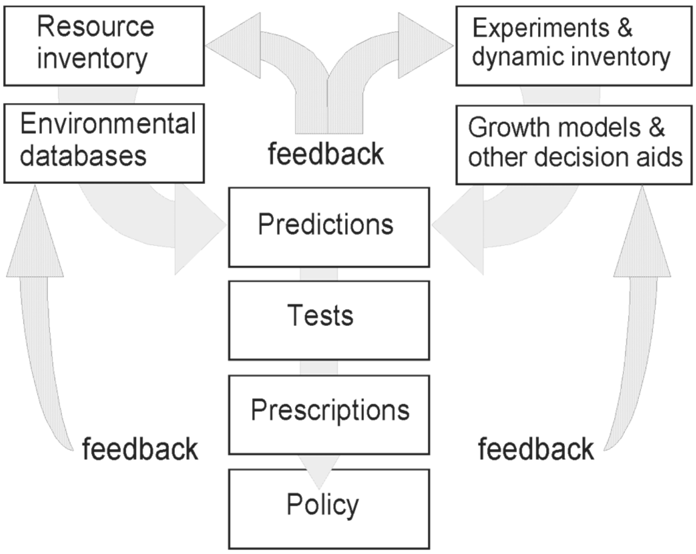


Figure 3. The role of growth models in decision making, forest management and the formulation of forest policy (Nix and Gillison 1985 cited in Vanclay, 1994)

2.4.1 Growth and yield tables

Yield tables are summaries of expected yields tabulated by stand age, site index etc. Growth tables are a variation more suited to uneven-aged stands, and tabulate expected growth according to various stand characteristics (Vanclay, 1994). A yield table anticipates yields from an even-aged stand and is one of the oldest approaches to yield estimation. Modern yield tables often include not only yield, but also stand height, mean diameter, number of stems, stand basal area and current and mean annual volume increment. Normal yield tables provide estimates of expected yields tabulated by stand age and site index for ideal, fully stocked or normal forest stands.

2.4.2 Growth and yield equations

It is important to understand the relationship between growth and yield. Growth refers to the increase in size of a population or an individual over a given period of time (e.g. growth in volume of a stand, in $m^3ha^{-1}yr^{-1}$). Yield refers to the final size of a population or individual at the end of a certain period (e.g. total volume produced by a stand, in m^3ha^{-1}) and usually includes any removal (e.g. thinning). A growth equation for even-aged stands predicts the diameter, stand basal area or total volume production attained at a specified time (i.e. age). Thus, a growth function may indicate that, at age 't', a stand is growing at (*dy/dt*) units per annum, where an equivalent yield function indicates that a stand at age 't' has produced 'y' units. The notation (*dy/dt*) simply means the change in 'y' observed during a very short period of 't' so that if ($t_2 - t_1$) span a very short time, Δt becomes very small, and $dy/dx = \Delta y/\Delta t = (y_2 - y_1)/(t_2 - t_1)$.

For growth and yield prediction models to be efficient, it needs to be flexible. Apart from being flexible, the growth function should be as simple as possible. It should also be able to predict both growth and yield either by integrating or by differentiating the yield function (Saramaki, 1992).

2.4.3 Types of forest models

Forest models represent average experience of how trees grow and of how forest structures are modified. The level of these models differs greatly. Tree models deal with morphological details of branching, stem form and root growth. Regional production models and stand growth models produce aggregate information about the development of a population of trees with a given set of environmental conditions and given intermittent modifications of stand attributes though human interference and other disturbances. According to Gadow and Hui (1998), four types of growth models are identified:

i. **Regional yield models:** Regional yield models are represented by highly aggregated yield-over-age equations. They are used in resource forecasting, especially for predicting the development of a given age class distribution in response to a series of periodic harvest levels.

ii. **Stand growth model:** Stand growth models require more information and, in turn, provide a greater degree of detail, including estimates of dominant height, basal area and stems per hectare. The development of an even-aged forest stand could be predicted using a stand model. Important variables are average or dominant stand height, the basal area and stems per ha. These basic quantities are used to derive secondary values, such as the quadratic mean diameter or stand volume.

iii. **Size class models:** The basic modeling unit in size class models is a representative tree impersonating a number of trees within a size class or cohort. Size class models, requiring even more information than stand models, are probably the most common type for stimulating alternative silvicultural programs.

iv. **Individual tree models:** Individual tree models utilize information about the position and size of specific trees and of the trees in their immediate neighborhood. The spatial information may be available in two or three dimensions. Three dimensional spatial models are used to quantify the amount of shading and constriction of growing space caused by neighboring trees.

2.4.4 Data requirement for growth modeling

Forest development is in direct response to various types and intensities of thinning, and is influenced by the environmental factors existing on the site. In sequence, two different kinds of empirical data are required for modeling. Firstly, data describing the change of state variables through thinning and secondly, data describing the change of state variables through natural growth. Growth data may be obtained from a variety of field experiments (Gadow and Hui*,* 1999).

Three types of growth trials may be distinguished with regard to the time horizon. Permanent plots are established for collection yield table data for a particular silvicultural program. The plots are re-measured, usually at regular interval, until harvesting. Temporary plots, measured only once, provide age-based information about relevant state variable, which is used to construct a yield table, again assuming normal or representative silviculture. Interval plots are re-measured once, thus providing an average rate of change in response to a given set of initial conditions. They may be abandoned after one measurement interval.

2.5 Tree-ring structure

Tree rings or growth rings referred to as tree rings or annual rings, can be seen in a horizontal cross section cut through the trunk of a tree. Growth rings are the result of new growth in the vascular cambium, a lateral meristem, and are synonymous with secondary growth. Visible rings result from the change in growth speed through the seasons of the year, thus one ring usually marks the passage of one year in the life of the tree. The rings are more visible in temperate zones, where the seasons differ more markedly (Stokets and Smiley, 1968).

A distinct growth ring boundary is formed for many tree species, in spite of the traditional belief that tropical rainforest trees do not produce ring (Lieberman *et al.,* 1985 and Whitmore, 1998). And various studies prove the occurrence of growth rings in tropical rainforest species throughout the world (Detienne, 1989; Vetter and Botosso, 1989; Worbe, 1999; Fichtler *et al*., 2003; Role and Pieter, 2005 and Somaue *et al*., 2008). The analysis of tree rings of tree in tropics is more complicated than that in temperate regions, as rings are not formed annually. The response to rainfall patterns varies among species often in relation to leaf-fall behavior (Borchert *et al*., 2002). In tropics, annual tree rings are more than often found in deciduous species than in semi-deciduous or evergreen species (Worbes, 1999).

The growth ring is divided into two parts, earlywood and latewood. As the names imply, earlywood tracheids are formed at the beginning of each growing season and during the period of rapid radial growth, whereas latewood trachieds are formed toward the end of the growing season when cambial activity slows down. In latewood, tracheid walls are thick and strong and appear dark in color, and their cavities become progressively smaller. It is the sharp contrast between the last-formed latewood cells of one growing season and the first-formed earlywood cells of the following season that delineates the boundary of an annual ring. Because of the sharp contrast between the two cell types, annual rings can be seen in most cross sections without magnification. Radiating outward from the center of the stem are rows of cells whose long axes are at right angles to the tracheids. These cells, appearing as horizontal bands are called rays. Their function is that of lateral condition. They are of interest to the dendrochronologist primarily because they are an aid in identifying the species of wood (Stokets and Smiley, 1968).

They have ring porous wood, and medium-sized and the rings are visible to the naked eye. In teak plantation of 15 years old, it has 57 % and 43 % of sapwood and heartwood, in 20 years old: 65 % and 35 %, and in 25 years old: 44 % and 56 %, respectively (CFC/ITTO, 2009).

2.5.1 The effect of site on tree growth

The growth of a tree is dependent on a complex series of interactions between genetic and environmental factors. The genetic makeup of the tree determines which environments the individual will tolerate and controls the response this tree will make to these environmental conditions. The environment supplies the nutrients, the water, and the radiant energy required for photosynthetic and metabolic processes. The abundance, or lack, of any one or all of these constituents determines whether the tree will grow to the limits of its genetic potential (Stokets and Smiley, 1968).

It was stated earlier that precipitation is the dominant growth-limiting climatic factor and that growth varies with the amount of precipitation. This is essentially true if the trees to be sampled are chosen with care. More accurately, the growth-limiting factor is the effective soil moisture content, which is defined as the amount of available surface water coming from all sources minus that lost through evaporation and runoff. The amount of effective soil moisture is controlled not only by the amount, type and timing of precipitation, but also by the texture, drainage, and composition of the soil (Stokets and Smiley, 1968).

If losses from runoff are low or local underground water is available to the trees, the effective soil moisture content will be sufficient in most years for a tree to produce optimum growth. When this occurs, the ring pattern is complacent – that is, there is insufficient variation in ring widths to produce any recognizable sequence. The sequence of rings may be uniformly wide or uniformly narrow. Trees growing under these conditions may be excellent botanical specimens, but they are useless for dating purposes. No permanent underground water is available for growth and the soil drainage is good, radical growth is nearly enough proportional to total precipitation to produce datable ring patterns.

III. MATERIALS AND METHOD

3.1 Location of study sites

The Bago Yoma is situated between N 16° 50′ 34" and 19° 29′ 34", E 97° 41′ 19" and 97° 13′ 27" (RS and GIS, 2006). It includes Bago (East) and Bago (West) Divisions, covering an extent of 9,556,142.73 acres (38672.49 km^2) (Figure 4). Administratively, Bago Yoma is divided into four districts; Bago, Taungoo, Pyay and Tharyawady Districts with 29 townships. It has 224.42 km at longest from north to south while 137.47 km across east to west. Streams and rivers formed at West Bago Yoma opened into the Ayeyarwady River which flows from north to south.

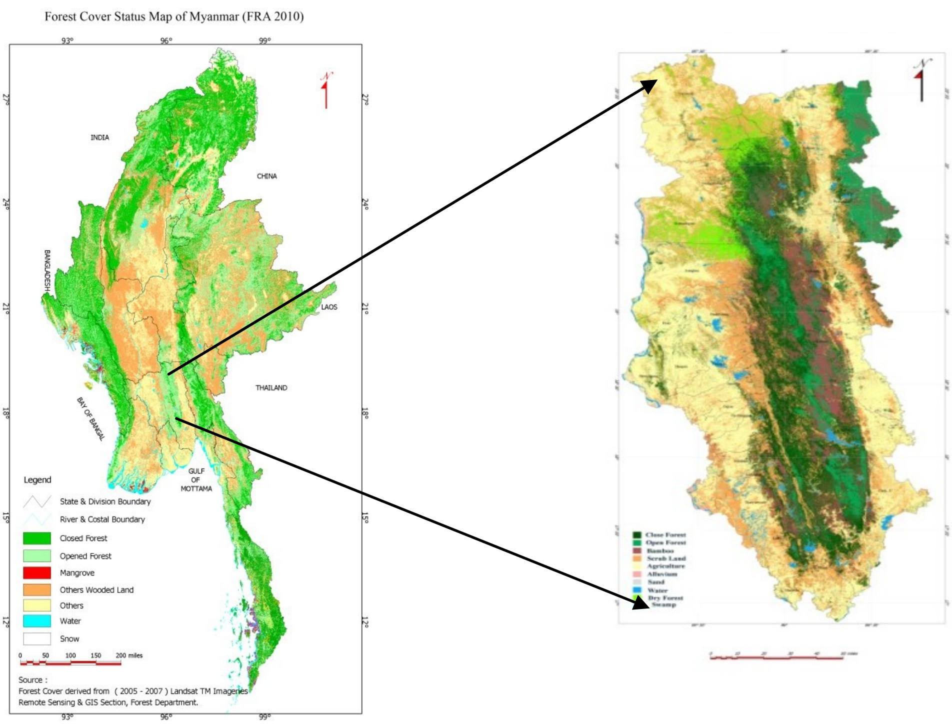


Figure 4. Map of Myanmar showing location of study site (Bago Yoma)

Naturally, location and other physical features made Bago Yoma as an ideal place for Teak. Elevation is fairly less than 1000 m forming undulating mountain ranges. Generally, slope is gentle at the valley bottoms and at the foothills whereas abrupt slopes and gorges can be found as elevation become higher. Sandy and loamy soils are common whereas alluvial soil can be found at the valleys and down streams forming fertile lands. Lateric and ferric soils are mostly found at west Bago Yoma and sometimes forming rock and boulders at the ridges except the south.

Both moist and dry deciduous species are widely distributed while other forest types such as evergreen and Inding (dry forest) are also found. Since Southern Bago Yoma receives more rainfall, moist deciduous forest dominated the region associated with some evergreen species whilst dry deciduous occurs at the north and higher elevation. West Bago Yoma hosts less commercially important trees compare with the East probably due to different sun aspect and soil quality. Indaing and dry forest species are dominant at the West except lowland areas.

The southwest monsoon from Indian Ocean brings rain from mid-May to mid-November. Mostly, rainfall is intense at the beginning and end for rainy season whilst a considerable drought period could be at the middle forming bimodal rainfall pattern especially in West site (Figure 5). Rainfall intensity is higher at the south and the east compare with the rest and the northwest region gained the least (RS and GIS, 2006).

3.2 Information of field study sites

The study was carried out in two places, namely Bago Township and Paukkaung Township, Bago Division, respectively (Figure 5). They are located in Bago Yoma Mountain region. Data collections are conducted in pure teak plantations in Reserved Forests which were established by the Forest Department of Ministry of Environmental Conservation and Forestry (MOECAF).

Bago township falls Bago District in the Easten Bago Yoma and situated between latitude 17° 37′ N and longitude 96° 13′ E. Three plantations are collected; 20 year old stand which is investigated in compartment no. 19, South Zarmani Reserved Forest, 15 year old stand in compartment no. 22, and 9 year old stand in compartment no. 14, Latpan Aung Mya Reserved Forest.

Paukkaung township which falls in Pyay District which is confined to the Western Bago Yoma and lies between latitude 18° 51′ N and longitude 95° 40′ E. There are four plantations; 20 year old stand in compartment no. 49, Middle Nawin Reserved Forest, and 25, 12 and 10 year old stands in compartment no. 29, 1and 2 of South Nawin Reserved Forest, respectively. The general descriptions of the studied plantations are showed in Table 3.

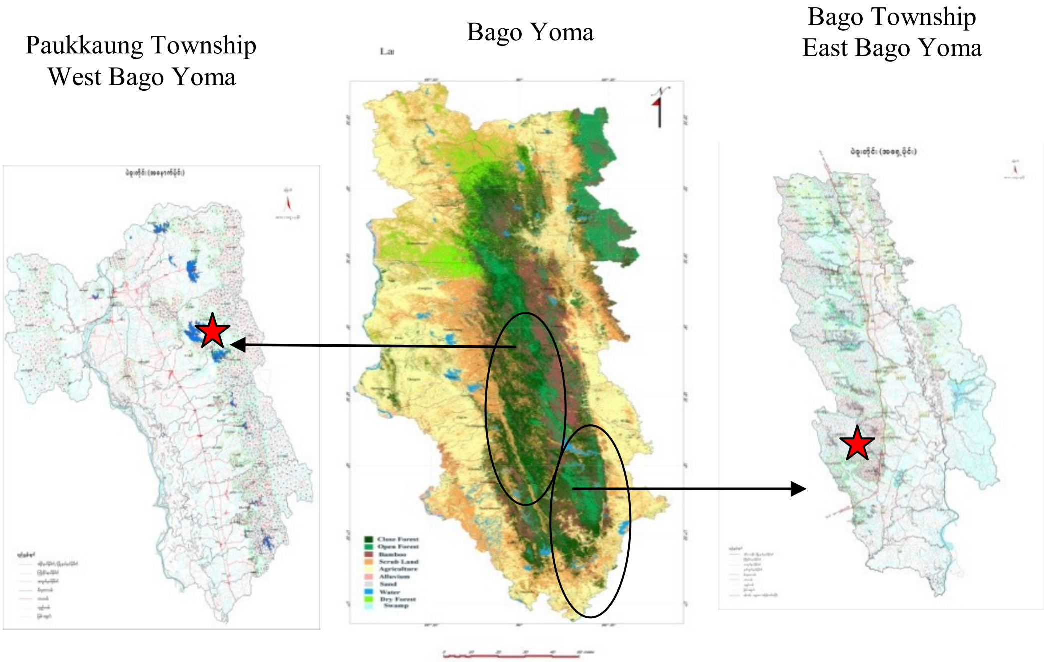


Figure 5. Location of study places

The climate of the study areas is greatly influenced by the monsoon circulating system and local topography. There is pronounced rainy season from May to October with ample rainfall coming from Bay of Bengal. Climatic data illustrated in Figure 5 was based on a 30 years record (1980 to 2010) of the Department of Meteorology and Hydrology (2011) for the study sites. The climatic characteristics of these study areas are shown in Table 2.

Table 2. Monthly mean temperature, mean precipitation and aridity index at Bago and Paukkaung according to De Martonne (1962)

	Bago			Paukkaung		
	Rainfall (mm)	Temp (˚C)	Aridity Index	Rainfall (mm)	Temp (˚C)	Aridity Index
Jan	1	24.1	0.39	1	24.2	0.41
Feb	2	26.0	0.67	2	26.3	0.50
Mar	17	28.6	5.18	2	29.5	0.71
Apr	34	30.8	9.90	17	31.8	5.00
May	281	29.8	84.69	128	30.8	37.78
Jun	678	27.6	216.78	203	28.3	63.69
Jul	736	27.0	238.65	186	27.9	58.83
Aug	708	26.7	231.67	212	27.9	67.26
Sep	444	26.9	144.20	179	28.6	55.64
Oct	181	27.6	57.89	115	28.8	35.38
Nov	50	26.6	16.52	59	27.3	18.95
Dec	6	24.2	1.96	3	24.8	1.04
Year	3138	27.2	84.44	1108	28.0	29.13

Source: Department of Meterology and Hydrology, Ministry of Transportation, 2011

De Martonne's aridity index is computed using the following relationship:

$$Am = (12*N) / (T+10)$$

where, A_m = Monthly aridity index

N = Mean monthly rainfall in mm

T = Mean monthly temperature in ˚C

A dry month can be defined by either having a monthly aridity index A_m below 20 or rainfall curve falls under temperature curve in climatic diagram according to Walter and Lieth (1967). Both classifications gave result of 6 dry months for both study areas.

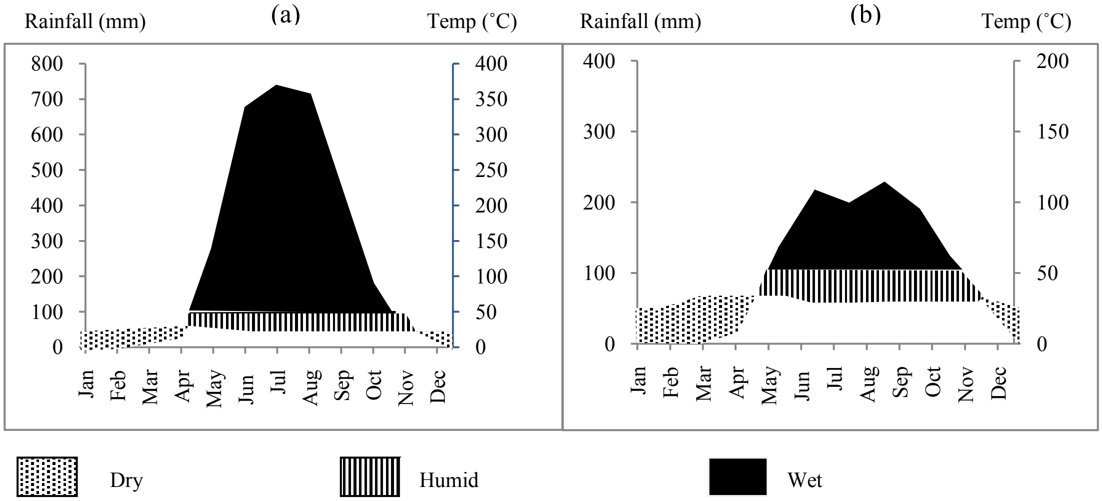


Figure 6. Climatic diagram of the study sites (1980-2010), Bago (a) and Paukkaung (b)

Table 3. Information of study sites

Location	Age class (yr)	Comp /RF	Altitude (m)	Latitude/ Longitude	Rainfall (mm)*	Temp (°C)**
Bago Township, Bago District, Bago (East)Division	20 yr	Comp. 19 South Zarmani RF	50	17° 37′ N 96° 13′ E	3138	27.2
	15yr	Comp. 22 Latpanaung Mya RF	60			
	10 yr	Comp. 14 Latpanaung Mya RF	95			
Paukkaung Township, Pyay district, Bago (West)Division	25 yrs	Comp. 29 South Nawin RF	320	18° 51′ N 95° 40′ E	1108	28.0
	20yr	Comp. 49 Middle Nawin RF	80			
	15 yr	Comp. 1 South Nawin RF	152			
	10 yr	Comp. 2 South Nawinb RF	140			

*Mean Annual Rainfall (1980-2010)
**Mean Annual Temperature (1980-2010)

3.3 Establishment of study plots and sampling

Sampling area was selected avoiding open area, streams, clearing for shifting cultivation. Data were collected in temporary sample plots which were rectangular in shape, and sample plot size was 2 % of actually plantation area according to national forest inventory (2010) (FAO, 2000). Sample size was 1.0 ha for each age class (Figure 7) and, total sample plots of 12 plots in Bago and 16 plots in Paukkaung.

Available history data of the plantations (plantation records) were collected for further references. All measured stands in both study sites were in Reserved Forests managed by Forest Department (FD). All stands in the sample plots of different ages were measured in height by Suunto dendro-clinometer, and diameter at breast height (DBH) was measured with a diameter tape. And about 20 of stands in the sample plots of each age class were selected randomly for taking the core samples. Two tree-ring cores per tree were taken by using increment borer at the breast height (1.3 m above the ground) of the stem with the aim of extracting all the tree-rings present in the tree. There were about 480 cores from Bago site plantations and about 640 cores from Paukkaung site for measuring tree-rings analysis.

In the sample plots of different age class, soil samples were collected by the instruction of soil section, Forest Research Institute (FRI), Yezin (Pritchett and Ohn, 1981). Soil samples were taken at the 0-50 cm depth by three sample points method (Making Forest Inventories, FAO 2000) in each sample plot. Total holes of soil were 36 holes in Bago site and 48 holes for Paukkaung site.

And the meteorological data (monthly rainfall and temperature), 30 years period (1980 to 2010), for both study sites were collected from the township Meteorology and Hydrology Department.

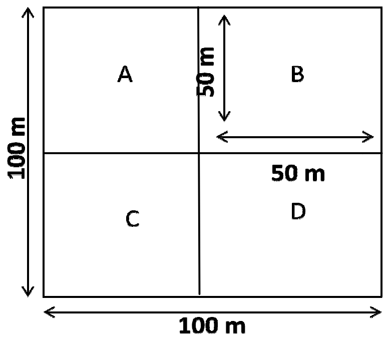


Figure 7. Layout of sample plot (1.0 ha)

According to the plantation records, it was found that, for all age class plantations, the seed were collected from the naturally growing teak tree from respective townships of the two study sites. Original data on diameter and height has been collected within the method of National Inventory that used in Myanmar National Forestry Inventory (2010). According to that manual, trees with diameter less than 5.0 cm are not included in measuring data. And also the trees less than 5.0 cm diameter in the plantations over 10 years old almost do not exist. Therefore, the stands which were less than 5.0 cm, do not exist in the plantations over 10 years old.

- **Total nitrogen (N) (%):** soil total nitrogen level was assessed by Kjeldahl method by using Labconco Kjeldahl, digestion and distillation unit.
- **Available phosphorous (P) (%):** on fine earth, available phosphorous levels were assessed with Double-acid extracting solution and phosphomolybdenium-blue complex method by using perkin-Elmer 55E, Spectophotomerer set at 600 mμ wave lengths.
- **Available potassium (K) (%):** on fine earth, available potassium levels were assessed with Double-acid extraction solution, by using Perkin-Elmer, Abomic Absorption Spectrophotometer 2280 set at 767 mμ wave lengths.
- **Calcium (Ca) (%):** assessed with double-acid extracting solution, by using Perkin-Elmer Atomic Absorption Spectrophotometer.

3.4.2 Measuring tree-ring width

Tree-ring width was measured (under the high magnification stereo-zoom microscope system with accuracy of 10^{-3}) to the nearest 0.001 mm using a computer-compatible tree measuring program (Measure J2X) and a x 40 stereomicroscope at Anatomy Laboratory of Forest Research Institute (FRI), Yezin, Myanmar.

3.4.3 Methods for estimating plantation growth

The data collected were put into Microsoft Excel Worksheets 2007, to suit the analysis package. The following equations were used to estimate the plant growth.

(1) Stand diameter distribution

(2) Stand density

(3) Volume calculation, $V = \pi/4 * d^2 * h * f$

where: V = tree volume, d = DBH, h = measured tree height, and f = form factor (0.45) (Perez and Kanninen 2005, Hlaing and Kyi 2009)

(4) Basal area calculation, $BA = \pi/4 * d^2$

where: BA = tree basal area, and d = DBH

Non-linear regression was used to constructe the stand diameter-height curves and growth cuves (for diameter, height, basal area, and volume) for each age;

(5) Michailoff height curve function,1943

$H = 1.3 + a . e^{(b/DBH)}$, where: H = expected tree height, a, b = parameters, e = exponential, and DBH = diameter at breast height

(6) Meyer function,1940

$H = a * e^{(-b * DBH)}$, where: H = expected tree height, a, b = parameters, e = exponential, and DBH = diameter at breast height

(7) The Richards function, 1959

$y = m\,(1 - e^{(-c * t)})^{n}$, where: y = growth parametes (height, DBH, etc.), m = upper asymptote, t = time, c & n = parameters, and e = exponential

(8) Gompertz function, 1825

$y = a^{*}\,(e^{(e(b-c\ *DBH))})$, where: y = growth parametes (height, DBH, basal area and volume), a = upper asymptote, b & c = parameters, and e = exponential

IV. RESULTS AND DISCUSSION

4.1 Soil properties in the plantations

Basic soil characteristics of plantations in both study sites are shown in Table 4. Accordint to result, there were significantly different in total nitrogen ($t_{Difference}$ =1.163, *df* =11, p<0.05) and calcium ($t_{Difference}$ =5.033, *df* =11, p<0.05) between both study site's plantations, but the rest soil properties that were tested in that study, were no significant. Thus it was found that the soil properites in both study sites were similar condition under the teak plantations. In Bago site plantations, although there were large variations in potassium, calcium, organic matter, sand, silt and clay among the plantations, variations in soil acidity (pH), total nitrogen and available phosphorous of the plantations were small (see supplementary Table S.1). In Paukkaung site, the content of soil properties were similar (Table S.2).

Table 4. Soil properties in both study sites

		Bago	Paukkaung
pH		6.1(0.17)	6.1(0.39)
Total Nitrogen	%	0.063(0.01)	0.047(0.01)
Ava Phosphorous	%	0.0003(0.0002)	0.0001(0.001)
Potassium	%	0.005(0.001)	0.005(0.001)
Calcium	%	0.15(0.02)	0.27(0.05)
Organic Matter	%	3.11(1.22)	3.23(1.00)
Particle size distribution	Sand%	67(5.62)	68(5.96)
	Silt %	18(1.88)	20(3.43)
	Clay %	15(1.94)	12(2.44)

Numbers are the means with standard deviation in the parentheses

Soil acidity (pH) influences nutrient uptake and tree growth. It is one of the factors affecting growth and distribution of teak (Kaosa-ard, 1995) and it directly affects several chemical and biological phenomena including the weathering of minerals, and the distribution of cations (Fisher and Binkley, 2000). Teak can grow well in these soil acidity conditions of both study sites eventhough it thrives best with the pH range of 6.5 - 7.5 (Gyi and Tint, 1998; Prichett and Ohn, 1981). In Bago site, the average pH of 20 years old plantation was 6.3, 6.0 of 15 years old plantation and 6.1 of 10 years old plantation. And the pH values were 6.0, 6.0, 6.1 and 6.2 of 25, 20, 12 and 10 years old plantations of Paukkaung site.

Plantations in Paukkaung site had more phosphorous, potassium, calcium and organic matter than in those of Bago site. On contrary, nitrogen content was higher in plantations of Bago site than in those of Paukkaung site. Bunyavejchewin (1983, 1987) and Singh (1998) suggested that better growth and highter stocked density was found on the soil with rich clacium and phosphorous under the teak plantations.Several studies elsewhere have also indicated that teak requires relatively large amounts of calcium for its growth and development, and thus named as a calcareous species (Seth and Yadav, 1958; Kaosa-ard, 1981; Tewari, 1992). The amount of calcium content in the soil was also used as an indicator of teak site quality, i.e. the greater the proportion of teak to other associate species, the higher the calcium in the forest soil (Bunyavejchewin, 1983 &1987). The high content of organic matter in all plantations in Paukkaung site may be due to the richness of calcium and phosphorus in the site as organic matter influences the physical and chemical properties of soil (Fisher and Binkley, 2000). There are many factors affecting the availability of phosphorus including parent materials, climate, mycorrhizal activities and microorganisms (Brady and Well, 2002; Troup, 1921).

Physical properties such as organic matter and sand, silt and clay were different among the plantations in Bago site ($p<0.0001$ for organic matter; $p<0.05$ for others, $df=11$). In Paukkaung plantations, there was variation in organic matter, sand and silt ($p<0.05$ for all items, $df=15$). On average, the particle size distribution percentage was very similar in sand (67 % and 68 %), silt (18 % and 19 %) and clay (15 % and 13 %) of both study sites. According to the soil mixture (Brady and Well, 2008), soil type of Bago and Paukkaung sites plantations were classified as sandy laom in all age classes.

The results of this study were similar with the past studies: Oo (2009) and Thet (1983) who studied soil properties of teak plantations in Bago Yoma (Table 5). However, compared with calcium per centage of other studies: 0.004 % at Takahashi *et al.*(2009) and 0.001 % at Ombina (2008), calcium percentage under the teak plantations in Bago Yoma is higher than that of their results.

Table 5. Soil properties of teak plantations in Bago Yoma according to Oo (2009) and Thet (1983)

		Oo (2009)	Thet (1983)	
pH		6.5	5.7	6.3
Total Nitrogen	%	0.10	0.08	0.10
Ava Phosphorous	%	0.0003	0.0002	0.0008
Potassium	%	0.0013	0.0075	0.002
Calcium	%	0.15	0.03	0.03
Organic Matter	%	8.7	6.5	5.1
Particle size distribution	Sand%	53	62	58
	Silt %	22	18	20
	Clay %	25	20	22

4.2 Stand diameter distribution

Diameter frequency distributions of teak stands in all studied plantations are developed (Tables S.3 and S.4). The Diameter class started at >5.0 cm with 5cm interval. In Bago teak plantations, in the diameter class of 15.1 – 20.0 cm in the 20 year old teak stand, most teak trees are found by making up about 37% of total. The tree in diameter class of 10.1 – 15.0 am of 15 year old and 5.1 – 10.0 cm of 9 year old constitute about 52 and 56 % of total, respectively (Figure 8).

Most teak trees were observed 34 % of total trees in the diameter class of 21.0 – 25.0 com in 25 year old in Paukkaung. There were 49 % of 15.1 -20.0 cm of diameter class in 20 year old stand. 10.0 – 15.0 cm diameter distributions of 15 and 10 year old have 52 and 53 % of total, respectively. In all plantations in both sites, diameter classes, i.e. > 25.1 cm have few trees (Figure 9).

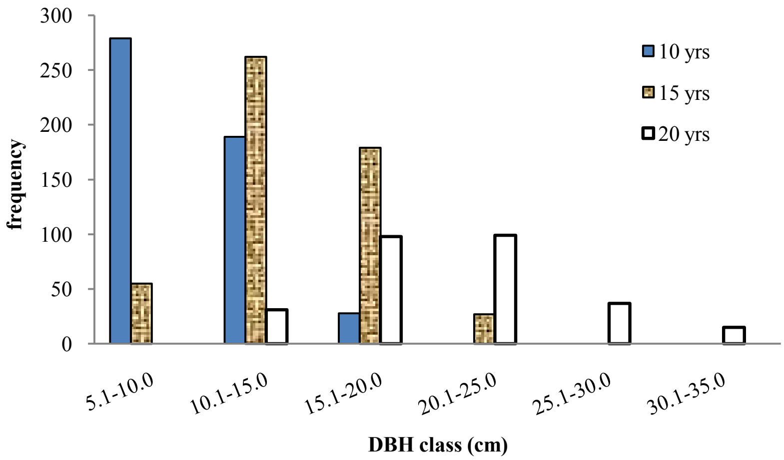


Figure 8. Stand diameter distribution of studied plantations in Bago

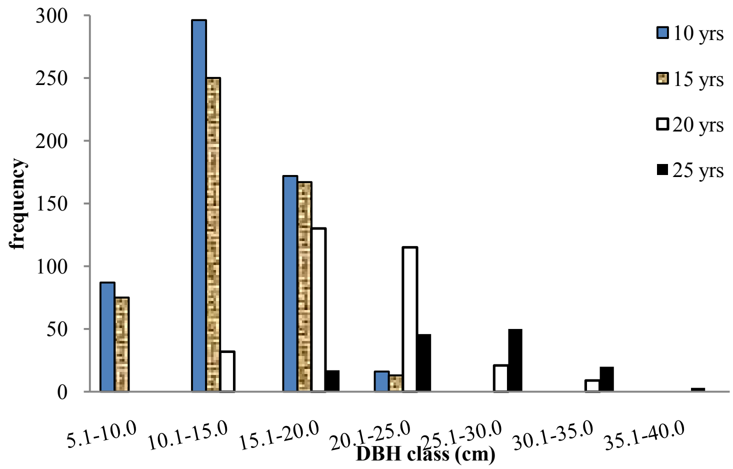


Figure 9. Stand diameter distribution of studied plantations in Paukkaung

Stand diameter distributions can be used as an indicator of the development stage of a forest. Prediction of stand diameter distributions is of value for forest researchers and forest managers. Diameter distributions of teak stands are particularly important as volume distribution is closely related to diameter distribution and tree stands which have received a variety of silvicultural treatments that would be a useful management tool to forecast the range of products.

It was observed that the range or distribution of diameter of the teak stands established on both study sites was considerably wider even within some age classes. Large variation was apparent in older stands, i.e. 20 and 25 years in both sites. The implication is that thinning has not been carried out on a regular basis in the respective stands (Table 6). Although Bago had fewer teak trees in each class than Paukkaung, trees were accumulated in smaller diameter classes in Paukkaung. A possible explanation is that teak stands in Paukkaung received more thinning but it was irregular and insufficient thinning at the early stages (Table S.6). Another most probable reason may be the illegal cutting of small size trees for firewood and other uses by local people in both sites.

Table 6. Current thinning schedule for teak plantations at 2.7 m x 2.7 m spacing for a 40 year rotation

Frequency of Thinning	Age (years)	Initial stocking (tree/ha)	Remaining stocking (tree/ha)	Thinning per cent	Thinning intensity (Grade)
1	~5	1336	668	50%	Heavy, from below (D)
2	~10	668	334	50%	Heavy, from below(D)
3	~15	334	250	25-30%	Moderate, from below(D)
4	~20	250	200	20%	Light, from below(D)
5	~30	200	110	50%	Heavy, from below(D)
6	40	110	0	100%	Clear cutting(E)

Source: Soe (2009) and FD, MOECAF (2011)

4.3 Stand density

The number of trees per hectare is a measure for the density of a stand. The total numbers of trees were decreasing with age in both study sites. The tree level information contained tree status (live or dead), original (planted or coppice), and diameter at breat height (DBH) and total height for all trees in the sample plot. Trees that were dead, defective at DBH, or processing a broken crown were not used in this study. Thus the number of tree in 10 years old is less stock than 15 years old plantation at Bago study site. The total number of trees per hectare in different ages of both study sites is shown in Figure 10 a & b.

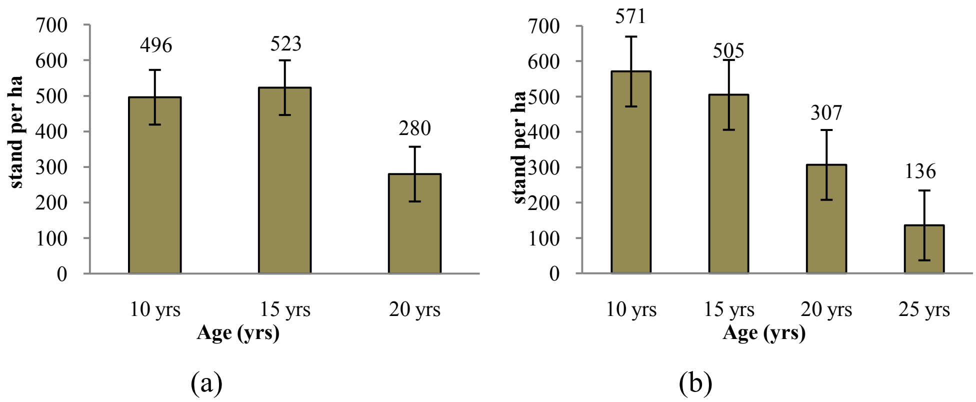


Figure 10. Stem density at different ages of study teak plantations at (a) Bago and (b) Paukkaung

Stand density is the number of trees growing on a unit area, i.e. per acre or per hectare. Stand density can describe how much a site is being used and the intensit of competition among trees for the sites' resources (i.e water, light, nutrients and space). At higher densities, the growth rates of individual trees slow down because there are more trees competing for the site's limited resources (Oo, 2009).

In both study sites, the same initial spacing was used in 10 and 15 years as 2.7 m x 2.7 m and in 20 and 25 years as 2.5 m x 2.5 m. All teak stands in both study sites received various thinning treatments (Table S.6). In 10 years old plantation in both sites, although 1st thinning had been done, the stand density was fewer than the stands at the departmental thinning insturction (see section 4.2, Table 6). However, the rest age classes of plantations had been given thinning at least one time (Table S.6), the remaining stand density was higher than the departmental thinning insturction. It is likely that there were also illegal cutting and utilization by the local people, and the plantations were given insufficient thinning operation.

4.4 Growth performance of study plantations

In this study, mean diameters and mean height of all plantations increased with the increasing age on both study sites. (Table 7). It was found that mean diameter and height of all teak stands investigated increased significantly with age on both sites except in the height of 15 and 20 years in Paukkaung. The average DBH of trees in Bago site ranged from 5.20 ± 0.12 cm to 37.10 ± 0.28 cm, and height was from 8.40 ± 0.34 m to 26.30 ± 0.10 m. In Paukkaung site, the average DBH ranged from 6.10 ± 0.13 cm to 37.80 ± 0.57 cm while avarage height was from 8.40 ± 0.07 m to 33.10 ± 0.53 m.

Teak stands on both study sites had more variation in basal area and volume than other growth parameters and they were depended on the stocking of area at that age and also on the thinning operation. At 20 years, teak had a basal area of 12.0 m^2 ha^{-1} and stocking of 280 trees ha^{-1} in Bago whereas the basal area of teak in that age in Paukkaung was found to be 7.21 m^2 ha^{-1} and 307 trees ha^{-1}. They have same site index 40 at the all age classes in both study sites. There was a significant difference ($p<0.05$) between plantations of the same age classes for both sites for diameter, height, basal area and volume performances (Teable 8).

The diameter increment of a tree on a given site is affected by many external factors such as stand density, crown position,climatic variation and soil fertility, genetic constitution of the planted teak trees or natural teak trees in the forest, etc. Their effect on growth may completely outweight the effect of age and whether there is any correlation between diameter and age (Tint and Schneider, 1980). It is clear that the tree grow slowly as they get older and that growth rate differ from place to place. The fastest growth recorded of teak plantations in the world is from Kapati, Bangladesh - 21 years old teak plantation had average heigth of 29.3 m and average diameter of 30 cm (Gogate, 1995). The hightest growth under plantation conditions in India was seen in Haldwani Division. At age of 20, the height growth was 23.1 m and diameter was 23.1 cm. Thus it is said that plantation teak grows slowly after an age of 15 years (Parameswarappa, 1995).

In this study, the average diameter of 10 and 15 years age plantations in Paukkaung were similar. But Paukkaung had larger diameter than Bago in 10 years old plantations. Generally average diameter in all age classes of both study sites were similar, but Bago had slightly higher height growth than Paukkaung eventhough there was same the genetic origins and site index 40.

At 10 years old, teak had average diameter of 13.7 cm and height of 12.0 m in Paukkaung site whereas the average diamter and height of teak in Bago were found 10.0 cm and 9.5 m. According to this study, Paukkaung study site plantations had similar with the other studies that conducted in Bago Yoma with annual rainall of around 2000 mm and 28.5˚C of annual average temperature, showed that 10 years old teak plantations had the average diameter of 13.4 cm and 11.7 m in height in the results of Oo (2007) and Soe (2009), respectively. And 15 years old plantations in this study of both sites appeared to be slightly lower diamter growth, but highter in height growth than Oo's (2007) finding of DBH of 15.5 am and average height of 11.8 m at 15 years. However, at 25 years old, teak had average diameter of 24.9 cm and height of 20.3 m in Paukkaung site. Teak plantations in study had lower growth in diameter and height as compared to Soe’s (2009) finding that had 31.2 cm in average diameter and 22.9 m in height. The difference could be explained by insufficient silvicultural treatments especially thinning. It can be inferred that teak trees were not heavily thinned in early ages.

Table 7. Growth performance of measured stands in Bago and Paukkaung (per hectare value)

Site	Age (yrs)	Current stocking (tree/ha)	Ave. DBH (cm)	Ave. Ht* (m)	total Basal Area (m^2)	total Volume (m^3)	Increment volume (m3 /ha/ yr) MAI	CAI	Site index**
Bago	10	496	10.0	9.5	5.31	25.02	2.78	6.34	40
	15	523	14.1	13.7	7.84	53.12	3.54	1.35	40
	20	280	20.6	15.2	12.00	82.08	4.77	1.14	40
Paukkaung	10	571	13.7	12.0	11.16	67.30	6.73	10.98	40
	15	505	15.2	14.3	9.54	62.46	5.21	0.23	40
	20	307	21.5	14.9	11.83	79.12	3.84	1.31	40
	25	136	24.9	20.3	7.21	84.52	3.38	1.10	40

*Total Height of tree

**Reference from Site Index Curves (Tint *et al.*, 1993)

Table 8. Analysis of variance (ANOVA) for all parameters in both sites showing mean square values and significant different level

Source of variance	DBH	Ht	Basal Area	Volume
20 yrs	26.19*	5.38*	0.005*	0.049*
15 yrs	54.25*	5.30*	0.503*	0.061*
10 yrs	29.89*	3.00*	0.001*	0.027*

(*) indicates significant differences at 0.05 level

4.5 Tree-ring width analysis

Tree growth deals with the increase in size over time, which is exhibited in a tree's diameter, height, basal area and volume. The growth rate of a species varies greatly with site, stand development patterns, and structure (Worbes, 1999; Kyaw, 2003b). In this study, to estimate the growth rate of plantations, around 60 sampled trees for each age class were used by analyzing tree-ring analysis in both study sites.

Worbes (1999) mentaioned that ring porous species like *T. grandis* have clearer rings than species with slight density vriations at the ring boundaries (e.g. Bombacaceae). However, tree-rings of teak in both study could be counted and measured for radial increment. The mean radial increment of teak plantations were 6.4 mm in 10 year old, 7.3 mm in 15 years, and 6.1 mm in 20 year old at Bago site, and also 9.5 mm, 7.0 mm, 5.7 mm, and 5.6 mm in 10, 15, 20 and 25 year old teak plantations, respectively, at Paukkaung site (Table 9 and figures 11 and 12). Ring increment (ring width) was significantly different among the same age class of plantations of different sites ($p<0.05$). This incidates that same species and age each have their own characteristics reactions and growth performance in response to the environmental conditions, such as rainfall and soil condition. Figure 13 illustrates the mean annual growth pattern of ring-widths of, e.g. 20 years old, teak plantations from both study sites. Ring-width curves showed similar growth rhythms but illustrated the characteristics variations between same age and same species, and different locations.

Table 9. Average tree-ring width (mm) of teak plantations in Bago

Site	Age class (yr)	DBH range (cm)	tree Height range (m)	Ave. growth ring width (mm)
Bago	10 yrs	12.0 -18.0	8.4 - 10.4	7.3 (1.8)
	15 yrs	17.0 - 27.0	11.5 - 15.9	6.4 (1.4)
	20 yrs	17.0 - 24.0	11.9 - 19.2	6.1(1.5)
Paukkaung	10 yrs	14.0 - 23.7	10.6 - 14.3	9.5 (2.0)
	15 yrs	14.0 - 20.0	9.2 - 17.4	7.0 (3.2)
	20 yrs	13.0 - 25.0	7.9 - 14.9	5.7 (2.5)
	25 yrs	17.0 -32.0	11.0 -33.0	5.6 (2.9)

Note: Standard devastations are in the parenthesis

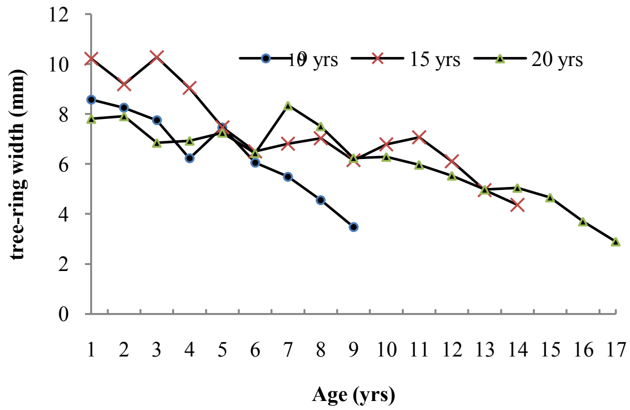


Figure 11. Tree-ring widths of teak plantations in Bago site

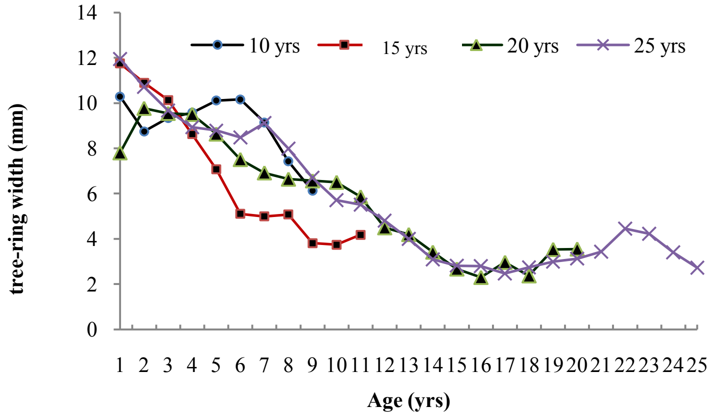


Figure 12. Tree-ring widths of teak plantations in Paukkaung site

Tint and Schneider (1980) reported that the mean radial increment of *T. grandis* tree (DBH 68 cm) in Myanmar was about 2.2 mm at the stump age of 155 years. In their study, the highest radial increment of 3.1 mm (Stump age = 110 years) was observed in alluvial moist teak forest in the Thayawaddy District, where the annual rainfall is about 2200 mm. Kyaw (2003) stated that the mean radial increment of *T. grandis* in Taungoo, Mebein, and Kanbalu was 2.4 mm (82 years), 2.0 mm (119 years), and 1.2 mm (86 years), respectively. According to this study finding, the ring width increment of the teak plantations was considerably higher than that of previous study findings, and also higher than Worbes' (1999) finding that was 5.2 mm in Venezuela. This is due to the age difference of the stands, and it shows that younger age trees could have a higher growth rate than older age. However, the diameter increment of a tree on a given site could be affected by many factor such as stand density, crown position, leaf area index and growth chatacteristics of species which could explain the decrepancy among studies on teak.

The patterns of individual increment curves of the same age class of difference sites were different from each other. This may be due to the result of prevailing light conditions: high light availablility (they have same spacing at initial stage but later they have different spacing and density depending on thinning) for some species leads to high increment rates of that species. Trees are usually in completion with their neighbours for light (Blasing *et al*., 1983) and they grow slowly with in juvenile and maturity stages (Worbe, 1999). Other possible factors are site suitability and growth characteristics of species such as leaf area, crown diameter, light demanding, shade tolerance and shade intolerance.

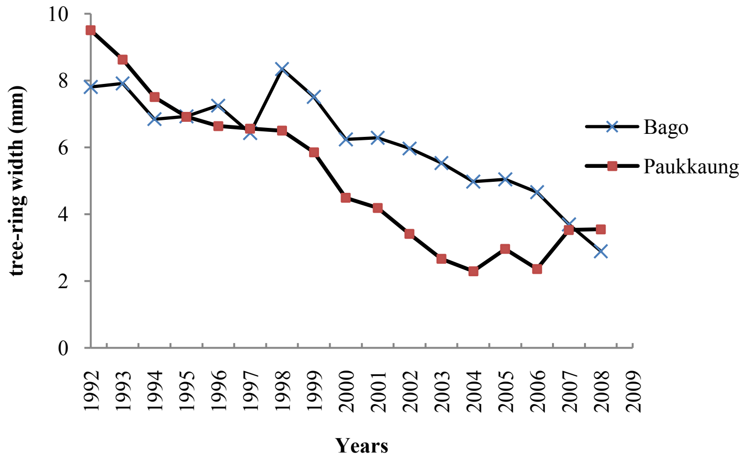


Figure 13. Mean annual increment of ring widths of 20 years old teak plantations from Bago and Paukkaung

In addition, the infulence of climate variations, thinning and tending activities also need to be considered when estimating the growth rate of tropical species. Tree growth and climate relationship revealed the important contribution of moisture index and rainfall rather than the direct infulence of the temperature on tree growth during different season (Somaru *et al*., 2008).

The tree-ring sites considered in this study are under the influence of the monsoon region. More than 95% at Bago and 90 % at Paukkaung , of the total rainfall were received during the monsoon months (May-October). Summer (pre-monsoon season: March-April) and winter (November-Febuary) were normally dry (hot) and warm. While a small amount of rainfall during these months was conductive for the new cell formation, warm (hot) and dry pre-monsoon season creates noticeable moisture scarcity which directly affects the tree growth (Somaru *et al*., 2008). The monsoon as well as the total annual rainfall have been reported to positively correlate with tree-ring width variations (Bhattacharyya *et al*., 1999, Sikder. 2003 and Somaru *et al*., 2008). But in this study, the general observations on relationship between the teak ring width variations and climatic parameters reveal that the low growth years (narrow ring) were significantly associated with deficient rainfall (drought condition).

Different time series of precipitation from the investigated study sites were correlated with the tree-ring chronologies. In both study sites, the sum of precipitation in rainy season (Monsoon period) (May to October) was positively correlated with teak growth (Table 11). The amount of water received during monsoon months (May to Oct) was the highest which moderates the temperature during these months and accelerates the photosynthesis as this was the peak growing season of teak (Chowdhury, 1964, cited in Somaru *et al*., 2008). Though the correlation analysis of data in Table 11 indicated that the relationship between tree-ring width and rainfall in term of annual rainfall, gave positive but it gave no significant coherent pattern. In general, annual temperature showed significant negative relationships with tree-ring chronologies of all studied plantations aged classes of both study sites. So Table 11 shows that the effect of direct infuence of temperature on tree-ring variations although the temperature is an important parameter in photosynthesis. However different time series of moisture indeces were positively correlated with the tree-ring (Table 10) but not strong and significiant, and but it gave coherent pattern with standardized tree-ring chronologies (Figure 14 and 15).

Table 10. Correlation coefficients between tree-ring width and annual moisture index

Site	Age class (yrs)	Pearson correlation
Bago	10 yrs	0.21
	15 yrs	0.42
	20 yrs	0.18
Paukkaung	10 yrs	0.58
	15 yrs	0.46
	20 yrs	0.36
	25 yrs	0.16

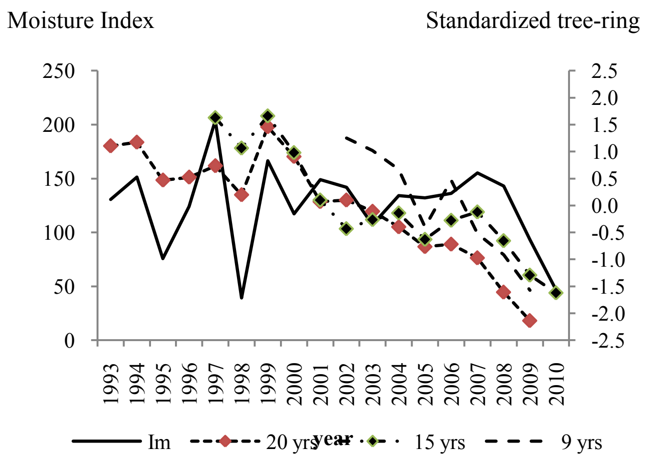


Figure 14. Comparison of standardized tree-ring width (mm) of investigated plantations with annual moisture index of Bago

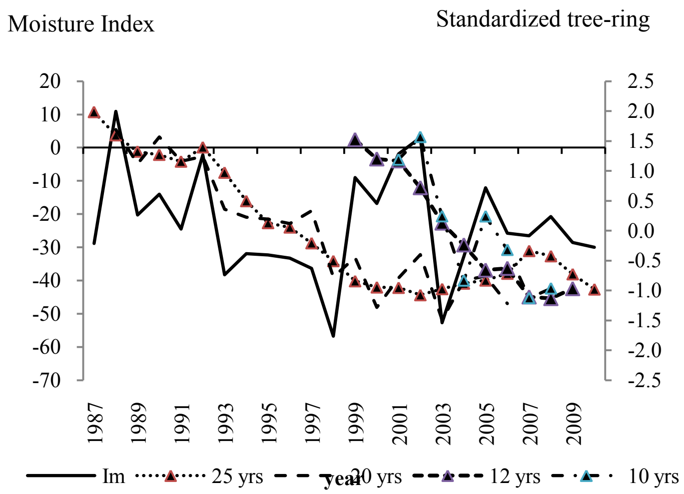
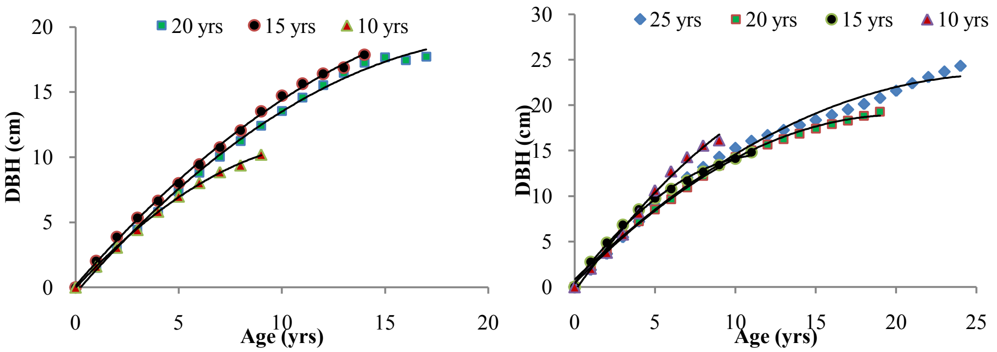


Figure 15. Comparison of standardized tree-ring width (mm) of investigated plantations with annual moisture index of Paukkaung

The diameter increment of a tree on a given site is affected by many external factors such as stand density, crown position, climatic variation, etc. (Kyaw, 2003b). Their effect on growth may completely outweigh the effect of age and weaver the correlation between diameter and age accordingly (Tint and Schneider, 1980). In this study, the current tree-ring width data from the measurement of core samples are concerned, the relationship between age (***A***) and diameter at breast height (***d***) of teak trees in the investigated stands of plantations ages can be expressed by the following functions (Tables 12 and 13, and Figure 16).



(a) (b)

Figure 16. Fitted diameter curves of the investigated teak stands of (a) Bago and (b) Paukkaung sites

All the polynomial function of age versus cumulative diameter growth showed the high coefficients of determination (R^2) for all different ages (Table 11). This indicates that diameter of the investigated tree of this study can be used as a reliable parameter to estimate the age of stand and vise versa.

Table 11. Correlation between tree-ring width and annual total rainfall and annual average temperature

Site	Age (yrs)	Average rainfall (mm)	Average temperature (ºC)	Average tree-ring width (mm)	Pearson correlation between tree-ring width and		# of sample
					RF (mm)	Temp (ºC)	
Bago	20	3211(478.1)	27.3(1.1)	6.1(1.5)	0.210	-0.405**	154
	15	3254(478.9)	27.3(1.2)	6.4(1.4)	0.285	-0.471**	141
	10	3330(284.4)	27.9(0.5)	7.3(1.8)	0.210**	0.545**	157
Pauk-kaung	25	1098(201.5)	28.0(0.4)	5.6(2.9)	0.426	-0.687**	161
	20	1072(243.9)	28.2(0.4)	5.7(2.5)	0.271	-0.524**	157
	15	1112(255.7)	28.3(0.5)	7.0(3.2)	0.532	0.482*	160
	10	1141(242.5)	28.2(0.5)	9.5(2.0)	0.643**	0.730**	160

Note: **Significant at 0.01 level (2-tailed)
* Significant at 0.05 level (2-tailed)
Standard deviations are in the parenthesis
RF= rainfall, Temp = temperature

Table 12. Coefficients of the polynomial function ($A=b_0+b_1d+b_2d^2$) and coefficients of determination for the diameter growth functions of different ages. A = stand age in year, d = diameter breast height in cm, b_0, b_1, b_2 = coefficients of the function

Site	Age(yrs)	b_0	b_1	b_2	R^2
Bago	10	-0.1059	1.8512	-0.0605	0.9995
	15	0.3557	1.9021	-0.0334	0.9992
	20	-0.3957	1.7343	-0.0274	0.9991
Paukkaung	10	-0.6813	2.3764	-0.0387	0.9955
	15	-0.6795	2.5773	-0.0955	0.9973
	20	-1.4392	2.1346	-0.0458	0.9989
	25	1.3161	1.9094	-0.0354	0.9922

R^2 = coefficient of determination

Table 13. Coefficients of the polynomial function (DBH = $b_0+b_1A+b_2A^2$) and coefficients of determination for the diameter growth functions of different ages. DBH = diameter breast height in cm, A = stand age in year, b_0, b_1, b_2 = coefficients of the function

Site	Age(yrs)	b_0	b_1	b_2	R^2
Bago	10	-21.7176	215.3801	-0.0534	0.9991
	15	-13.6478	134.9911	-0.0334	0.9992
	20	-11.2181	110.9512	-0.0274	0.9996
Paukkaung	10	2.0558	-22.4071	0.0061	0.9844
	15	-38.5553	383.7531	-0.0955	0.9973
	20	-16.9525	168.6001	-0.0419	0.9968
	25	-14.2964	142.2823	-0.0354	0.9922

R^2 = coefficient of determination

4.6 Stand diameter-height curves

Whereas the DBH is a function of age and silvicultural treatments, height is an indicator of the quality of the site (climate, soil, exposition) and is rarely influenced by silvicultural treatments (Oo, 2009). Basically stand height is used to determine the site index or site class of a stand, to estimate the volume of standing trees and to predict the future growth from stand characteristics (Van Laar and Akca, 2007).

In this study, at first to estimate diameter-height curves, Michailoff (1943) , Meyer (1940) and Exponential fit functions were used (Tables S. 7 and S. 8). Although there were functions that had been proposed to fit height curves, Michailoff (1943) function gave the better result than others because it had asymptotic properties to obtain a good fit to the data. Stand height curves were developed for each stand in both study sites. But the coefficient of determination (R^2) was found to be lower in all different ages of plantations in both study sites (Table 14) similar to the finding of Soe (2009) who used the Michailoff's function for diameter-height curves. This is because of limited data collection and time series of age classes. But Wang *et al*. (2007) reported that error in estimation can be reduced to minimum by employing site-specific equation. However Perez (2005) stated that best-fit models developed for one zone cannot be used for another zones. So the site-specific equation was calculated for all study plantations in both sites.

The relationship between diameter and height within an even-aged stand is curviliner. However nonlinerity is not always detectable. This can be due to an insufficient sample size that is too small to detect lack of fit of th linear model, or to excessive random variability of tree heights within a given diameter class, which is sometimes caused by inaccurate height measurements. Many nonlinear regression models, the majority being linearizable by a transformation of variables, have been proposed to fit a stand height curve. The fitted curve should satisfy certain requiremnts, such as the function being monotone increasing with increasing DBH (Van Laar and Akca, 2007).

Table 14. Parameter estimations of stand height curves (using Michailoff height curve function: $y=1.3+ a * \exp^{(b/x)}$, y= height, x = DBH, a & b = coefficients of the function)

Site	Age class (yr)	Coefficients		r	R^2	RSS
		a	b			
Bago	10	7.79	-0.02	0.53	0.34	0.00
	15	8.96	-0.03	0.64	0.41	0.00
	20	10.89	-0.02	0.66	0.44	0.00
	All	**22.52**	**-8.42**	**0.82**	**0.68**	**0.25**
Paukkaung	10	8.74	-0.02	0.59	0.35	0.00
	15	0.64	-0.03	0.69	0.48	0.00
	20	8.29	-0.02	0.72	0.52	0.00
	25	8.22	-0.04	0.87	0.75	0.00
	All	**23.53**	**-6.77**	**0.78**	**0.61**	**2.08**

R^2 = coefficient of determination; RSS = residual sum of squares

Then the best function was found for estimating of diameter-height curves as quadratic fit function. The relationship between the DBH and Ht of each tree was constructed to estimate the height curve of plantation at the existing age classes with non-linear regressions, quadratic fit. The functions of the sample trees from the different ages of both study sites showed stronger relationships with higher coefficients of determination (R^2) than those obtained from Michailoff's function (Table 15). The results suggest that the quardratic fit function to be suitable for all age classes in both study sites (Tables 15 and 16, and Figures 17 and 18). However, with more samples and time series for investigated stands, the Michailoff function is recommended for analysis of diameter-height relationship.

Table 15. Coefficients estimations of stand height curves by comprising Michailoff function and quadratic fit function

Site	Coefficients					Function
	a	b	c	r	R^2	
Bago	22.52	-8.42		0.82	0.68	Michailoff
Paukkaung	23.53	-6.77		0.78	0.61	
Bago	5.15	0.55	-0.01	0.97	0.94	Quadratic fit
Paukkaung	12.04	-0.27	0.02	0.98	0.96	

R^2 = coefficient of determination

Table 16. Comparison of the actual data and theoretical (calculated data) data by using quadratic fit function for diameter-height estimation

		Bago			Paukkaung			
		10 yrs	15 yrs	20 yrs	10 yrs	15 yrs	20 yrs	25 yrs
	DBH (cm)	10.0	13.8	19.6	13.7	14.1	20.5	24.9
Actual	Ht(m)	9.5	14.1	15.7	12.0	13.0	14.9	20.3
Theoretical	Ht(m)	9.6	11.4	14.9	12.1	12.9	14.5	17.7

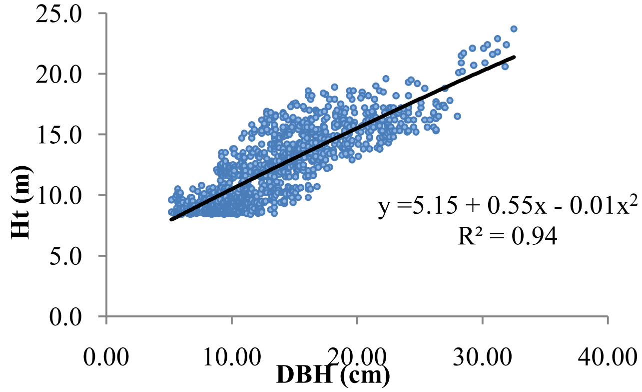


Figure 17. Diameter-Height curves of investigated teak stands in Bago plantations

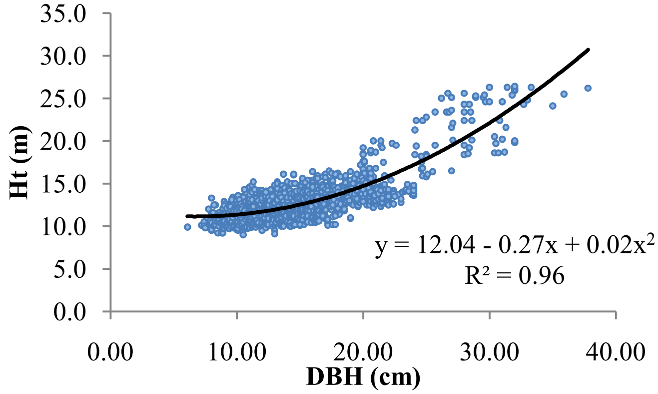


Figure 18. Diameter-Height curves of investigated teak stands in Paukkaung plantations

4.7 Stand growth curves

In this study, data were collected from temporary sample plots. For stand growth parameters such as diameter breast height, height, basal area and volume , Richards (1981), Gompertz (1825) and Logistics were used (Tables S.9 and S.10). Among these functions, Richards (1981) gave the better results than other functions according to the important statististical parameters for selecting the most suitable regression curves, the standard residual and the corfficients of determination (Table 17). Schmidt (2009) suggested that the Richard function was used to develop the growth curves since the function has been widely used in forestry because of its flexibility, accuracy, and meaningful analytical properties because the Richards function has four functional parameters (a, b, c and d), with t as time.

Then , as compared the growth performance of actual and calculated results for both study sites (Table 18), the differences were found in basal area and volume of both study sites plantations (Table 19). It should be noted that the actual growth results are not based on consecutive measures in permanent sample plots and short time periods (Vanclay, 1991).

Table 17. Coefficients estimations of stand growth curves (using Richards function: $y = a/(1+\exp^{(bc*x)})^\wedge(1/d)$: y = growth parameters (diameter at breast height, height, basal area, volume), a = asymptote, b = growth rate constant, c & d = coefficients) of teak plantations in Bago and Paukkaung sites

Site	Parameters	Coefficients				r	R^2	RSS
		a	b	c	d			
Bago	DBH	146.81	1.00	0.03	3.65	0.76	0.58	0.05
	Height	21.54	1.00	0.13	1.05	0.84	0.71	0.09
	Basal area	262.20	5.86	0.11	0.81	0.73	0.53	0.00
	Volume	102.91	3.25	0.16	0.63	0.70	0.50	0.02
Paukkaung	DBH	81.21	1.00	0.15	3.37	0.69	0.48	1.96
	Height	14.29	1.00	0.23	0.93	0.60	0.36	0.06
	Basal area	307.80	5.23	0.03	0.30	0.71	0.50	0.45
	Volume	245.05	3.62	0.13	0.52	0.72	0.52	2.71

R^2 = coefficient of determination; RSS = residual sum of squares

Table 18. Growth performances by using Richards function of teak plantations in Bago and Paukkaung

		Bago			Paukkaung			
		10 yrs	15 yrs	20 yrs	10 yrs	15 yrs	20 yrs	25 yrs
Actual	DBH (cm)	10.0	13.8	19.6	13.7	14.1	20.5	24.9
	Ht (m)	9.5	14.1	15.7	12.0	13.0	14.9	20.3
	BA (m^2)	5.3	7.8	12.0	11.2	9.5	11.8	7.2
	Vol (m^3)	25.0	53.1	84.8	67.3	62.5	76.8	84.5
Theore-tical	DBH (cm)	13.7	15.3	16.9	14.9	18.6	21.1	22.6
	Ht (m)	12.0	15.0	17.3	10.1	13.2	15.1	15.3
	BA (m^2)	2.8	4.8	8.3	7.0	8.0	9.1	10.4
	Vol (m^3)	26.4	49.2	80.1	40.6	70.8	117.4	180.8

Table 19. Independent-sample T test for all parameters of plantations in both sites showing mean square values and significant different level

Source of variance	Bago	Paukkaung
DBH (cm)	0.700	2.001
Ht (m)	2.779	2.641
Basal Area (m^2)	9.401*	1.626*
Volume (m^3)	5.920	877.641**

(*indicates significant different at 0.05 level and ** at 0.01 level)

In growth curve estimation, it wasfound similar condition of diameter-height estimation. Thus to fit the growth curves for the existing age classes of study sites, site-specific equation was developed. The quadratic fit function for growth parameters showed the high coefficients of determination (R^2) for all different ages (Table 20) when compared as actual results (Table 21 and Figures 19 to 22). And alos, based on the finding of this study, the Richards function could give the signnificant correlation to the actual results if the data collection was continuous time series measurement and more observations, like mentioned in the diameter-height relationship.

Table 20. Coefficients estimations of stand growth curves by quadratic fit function: [$y = a+bx+cx^2$, y = growth parameters (diameter at breast height, height, basal area, volume), x = age (year), and a, b & c = coefficients] of teak plantations in Bago and Paukkaung sites

Site	Growth parameters	Coefficients a	b	c	RS	r	R^2
Bago	DBH (cm)	9.585	-0.0418	0.048	0.00	0.99	0.98
	Ht (m)	1.951	0.942	-0.012	0.00	0.99	0.99
	BasalArea (m2)	0.020	-0.002	0.001	0.02	0.94	0.88
	Volume (m3)	0.076	-0.015	0.001	0.02	0.98	0.97
Pauk -kaung	DBH (cm)	17.049	-1.063	0.057	0.00	0.96	0.92
	Ht (m)	22.528	-1.608	0.060	000	0.93	0.86
	BasalArea (m2)	0.035	-0.003	0.001	0.01	0.98	0.89
	Volume (m3)	0.521	-0.070	0.003	0.03	0.93	0.86

R^2 = coefficient of determination; RSS = residual sum of squares

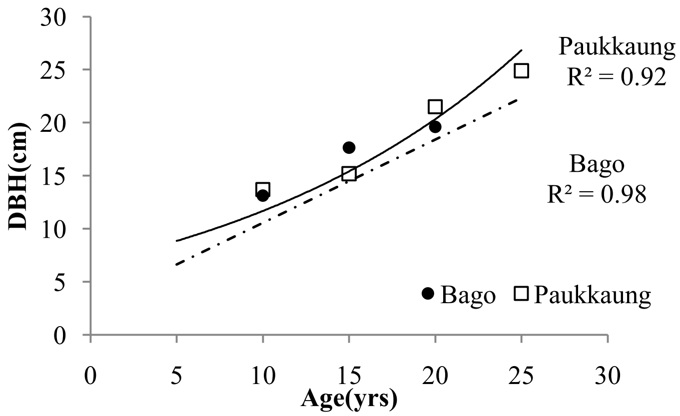


Figure 19. Fitted mean diameter curves of the investigated teak stands of Bago and Paukkaung

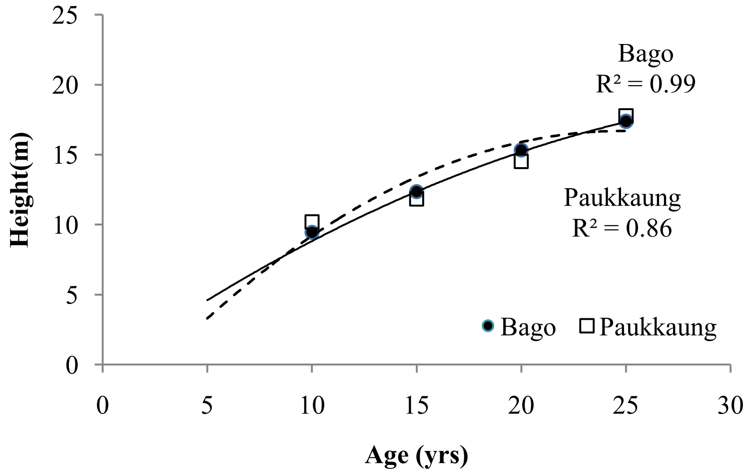


Figure 20. Fitted height curves of the investigated teak stands of Bago and Paukkaung

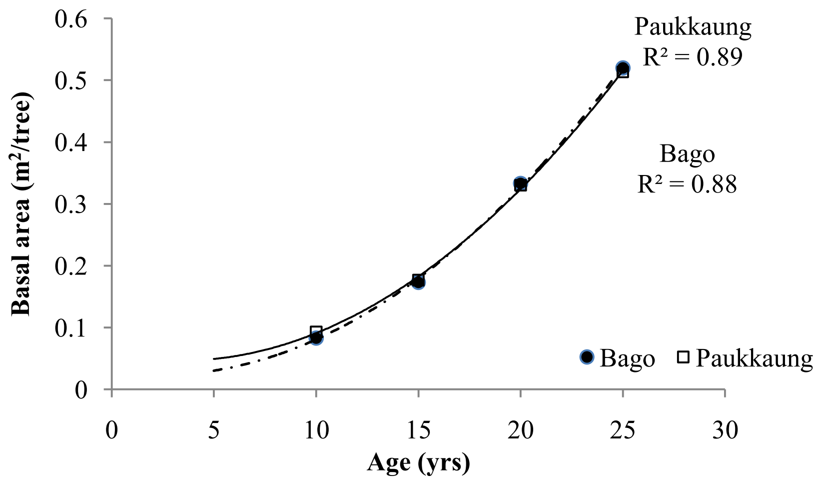


Figure 21. Fitted basal area curves of the investigated teak stands of Bago and Paukkaung

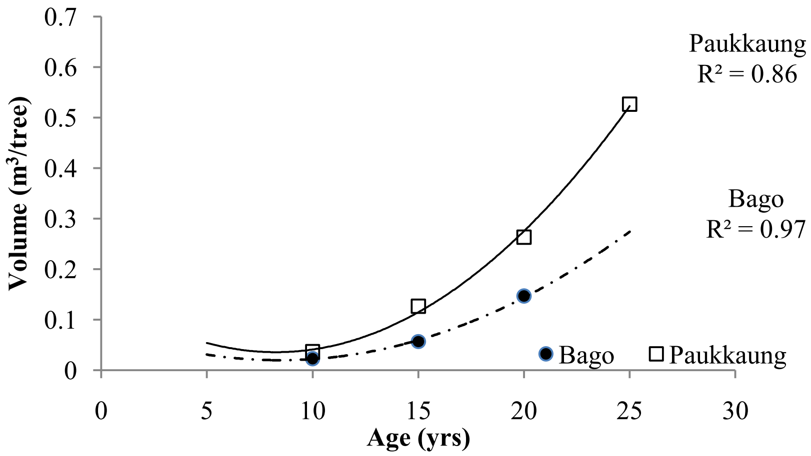


Figure 22. Fitted volume curves of the investigated teak stands of Bago and Paukkaung

Table 21. Comparison of the actual data and theoretical (calculated data) data by using quadratic fit function for stand growth estimation

	Growth parameters	Bago			Paukkaung			
		10 yrs	15 yrs	20 yrs	10 yrs	15 yrs	20 yrs	25 yrs
Actual	DBH (cm)	10.0	13.8	19.6	13.7	14.1	20.5	24.9
	Ht (m)	9.5	14.1	15.7	12.0	13.0	14.9	20.3
	BA (m^2)	5.3	7.8	12.0	11.2	9.5	11.8	7.2
	Vol (m^3)	25.0	53.1	84.8	67.3	62.5	76.8	84.5
Theoretical	DBH (cm)	10.2	14.1	20.5	12.5	14.0	18.7	26.2
	Ht (m)	10.2	13.4	16.0	12.0	12.5	14.5	20.1
	BA (m^2)	5.3	8.6	10.3	8.7	9.3	10.7	6.3
	Vol (m^3)	20.2	55.9	74.1	53.1	46.3	62.6	85.0

Tree growth basically deals with the increase of size with time, which is the increment of diameter, height, basal area and volume. In Myanmar, the main objective of teak plantations establishment is to produce hight quality timber in tree with good or acceptable growth rates. To achieve that objective, the plantating site must be suitable for the growth and development of teak. In general the performance of plantations depends largely on the condition of the planting site. Plantations established on good sites have higher growth and yield potential than those on poor or unsuitable sites.

Growth parameters of teak stands in Paukkaung were comparatively greater than those of teak stands in Bago at the same aged classes and they had significant variation in DBH, basal area and volume ($p<0.05$) (Table 22) except height. It may be due to the fact that teak stands in Bago site received less silvicultural treatments than those in Paukkaung site since diameter is mainly influenced by ecological conditions (rainfall, temperature and soil conditions) and silvicultural treatments in addition to age. However, there was no significant different between height growth ($p>0.05$). It may be due to the fact that they have same site index and good site conditions for teak plantations.

Table 22. t value difference and *df* of the growth parameters at 0.05 level by using independence-sample t test for comparing growth parameters of both sites

Age (yrs)		DBH	Ht	Basal area	Volume
10	$t_{Difference}$	18.180	31.662	16.761	18.651
	dt	1036	1036	1036	1036
15	$t_{Difference}$	1.040	2.746	0.745	1.241
	dt	981	981	981	981
20	$t_{Difference}$	2.462	14.626	2.647	4.863
	dt	519	519	519	519

Stand basal area can be used to estimate stand volume and is a useful measure of the degree of competition in the stand. It is often quoted when planning thinning prescriptions. The basal area of trees per unit area is only governed by the size and density of trees. Basal area of teak trees in this study was large variation among all age classes in both study sites (see section 4.4, Table 7). It might be due to stocking of the stands and different thinning treatmnets in each study area, resulting in inconsistencies in basal area of those stands. If these stand were allowed to develop for 40 years, rotation of Special Teak Plantation Programme, Paukkaung could have higher basal area than Bago.

Tree volume is the most important characteristic to estimate the growth and yield of the individual trees or stands. In managing a forest stand for commercial timber production, an estimate of the volume of wood it contains is essential. The development of volume growth dynamics of teak in different sites could aid decision on the length of rotation or on the choice of exploitable size (Kyaw, 2003b). In this study, it was found that Bago had a volume of 84.8 m^3 ha^{-1} and stocking of 280 trees ha^{-1} while Paukkaung had 76.8 m^3 ha^{-1} and 307 tree ha^{-1} at the age of 20 years. Tree volume of this study was lower than Oo's (2007) finding that was 170.6 m^3 ha^{-1} with 442 trees ha^{-1} at the age of 25 years. It is mainly due to the difference in stocking of these two study areas. Like diamter height, it was also apparent that basal area and volume growth of teak stand studied are noticeable better in Paukkaung than in teak stands investigated in Bago (Figures 19 to 22 and section 4.4, Table 7).

V. CONCLUSION

Due to shrinking of the natural forest including the natural teak forests, teak plantations are established with a view to enhancing the natural stock of teak without destroying the existing environmental conditions. Teak plantations have been established on an extensive scale on degraded as well as depleted lands to restore forests and build up a wood capital for the future.

In Myanmar, teak plantations are mainly concentrated in the Bago Yoma region, a place legendary for its natural teak forests and where extensive teak plantations programs have been implemented. This study was conducted to investigate the growth of teak stands established at two different aspect of Bago Yoma; the first study site, namely Bago Township, located in the East Bago Yoma which has above 3,000 mm annual rainfall and the second study site, Paukkaung Township, situated west site of Bago Yoma having over 1,000 mm annual rainfall. Both sites have similar annual temperatures. Three age classes of plantations: 10, 15 and 20 years old plantations in Bago site and four age classes such as 10, 15, 20 and 25 years old in Paukkaung site were observed.

This study reveals that both study sites are suitable for the establishement of teak plantations considering climatic data mainly rainfall and temperature. Site selection for teak plantations is acceptable because it was found that all investigated stands were established on sandy loam soil and site index 40. It suggests that site-species matching was exactly exercised in both study sites. As a result, teak tree grow well on both sites in general. The study concludes that teak stands has shown resonable growth in both sites despite indequate maintenance such as thinning that was not carried out regularly in both study sites. Accordingly, teak plantations should be thinned regularly and heavily as required, particularly in young ages, i.e, the first half of the rotation (40 years at Special Teak Plantations Program).

Illegal cutting and theft problems in teak plantations were found in both study sites. Teak plantations are normally established in reserved forests which are protected by the existing Forest Laws (1992). However, teak plantations, especially accessible ones, are still subject to illegal cutting where poles and posts are of great local demand. Therefore, local people participation in the establishment of forest plantations is curcial. In addition, legal, institutional and social issues should be adequately addressed to achieve effecitive protection of teak plantations against illegal cutting.

Based on this study findings, Hypothesis 1 is accepted, because the growth of plantations at the same age classes in both sites were found different and the growth parameters of plantations in Paukkaung site, as compared to that of Bago site, has better performance in term of diameter, basal area and volume, except of height – same site index 40. Hypothesis 2 is rejected because the rainfall-growth relationship was not significant, although positive with age classes in both sites, and temperature was significantly negative related to tree-ring width in all aged classes of plantations of both study sites.

The most suitable site-specific function for the investigated aged class of this study sites was quadratic fit function because of few data collection and short time series of age classes. However Michailoff (1943) function for diameter-height relation curve and Richards (1981) function for growth analysis can be used to investigate growth and yield tables for these study sites if the data collection are based on consecutive measures and more observations in permanent sample plots because they gave best results over all age classes in both study sites. All results shown reasonable growth in all age class plantations as compared with yield table of teak plantations (Tint *et al*., 1993) (Table S.5) and also Bago Yoma is a native for teak with favorable conditions such as topography, weather, and soil.

The present finding are from Bago and Paukkaung sites, so it does not represent teak plantations in other part of Bago Yoma Range and also other parts of the country. Thus the results are subject to the local environmental conditions of the study areas. Further research would be useful for assessment of growth performance in different regions with different enviornmental conditions to establish the linkages between site, silvicutural treatment and volume production with continual management and measurement .

According to the rainfall-growth analysis of teak stands, there is a dependence of tree growth on the amount and the distribution of precipitation. Rainfall is required for the tree radial growth and the variation of the length of the growing period is reflected in the width of the tree-ring. This present study can contribute information to attempt the network of teak dendrochronologicaes in Myanmar.

The main limitations of the study are:

-the study was conducted in two locations, Bago and Paukkaung with distinct climatic condiotions especially rainfall level, and as such results are subject to local enviornmental conditions.

-although plants were of the same genetic origin, site conditions and initial spacing, thining records were not taken in permanent sample plots which could explain some of the discrepacies in the results of this study.

There is a need to,

-localize the diameter-height relationship in order to make it more suitable for specific teak stand

-investigate growth performance of commercial plantations at the regional level

-establish intensive plantations rather than extensive for adequate maintenance and silvicultural management especiall thinning

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APPENDICES

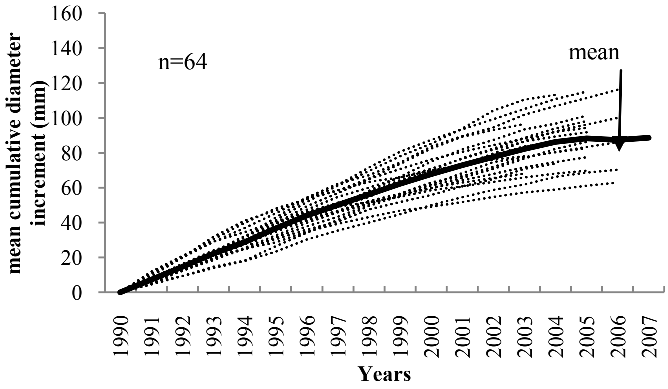


Figure S.1. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 20 years age class plantation in Bago

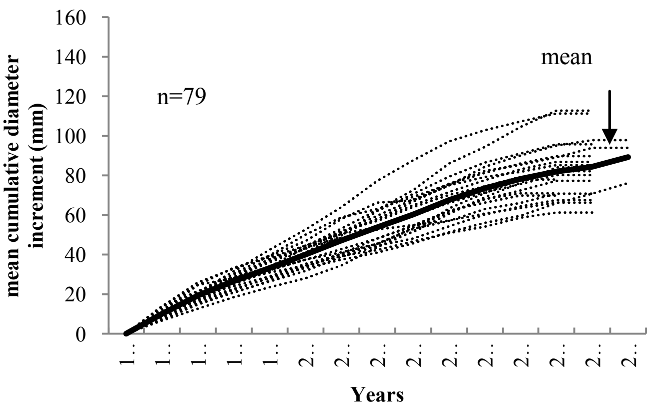


Figure S.2. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 15 years age class plantation in Bago

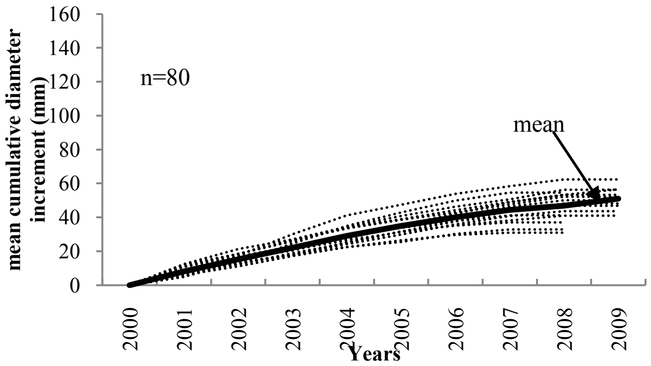


Figure S.3. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 10 years age class plantation in Bago

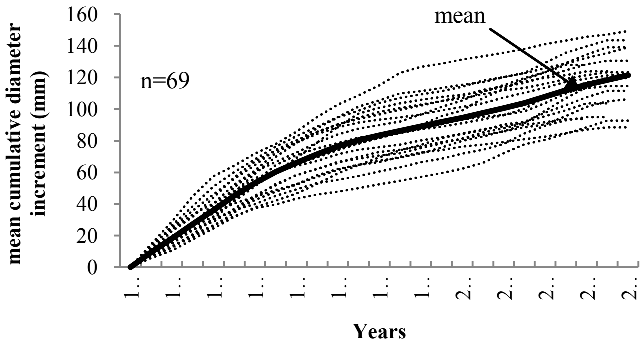


Figure S.4. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 25 years age class plantation in Paukkaung

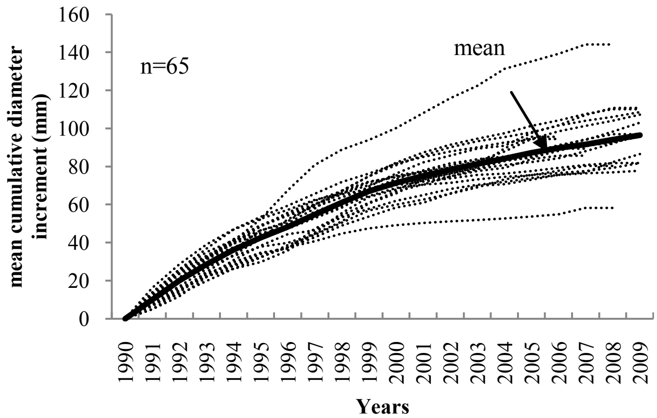


Figure S.5. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 20 years age class plantation in Paukkaung

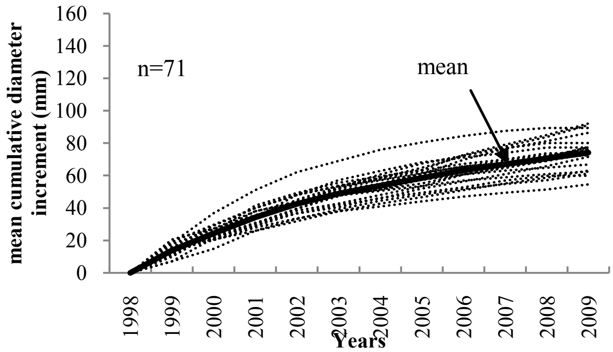


Figure S.6. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 15 years age class plantation in Paukkaung

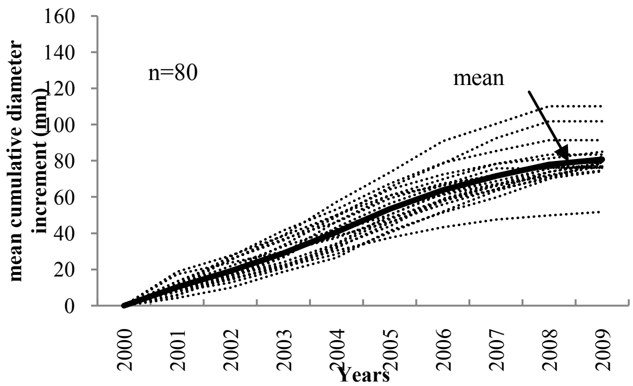
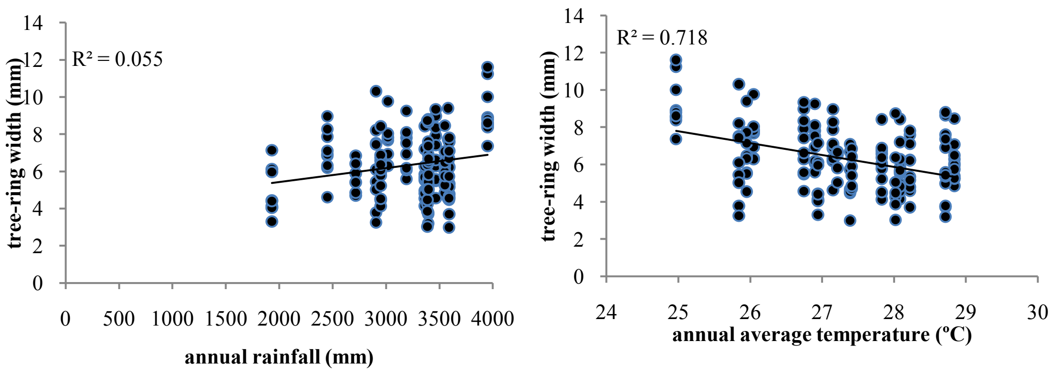
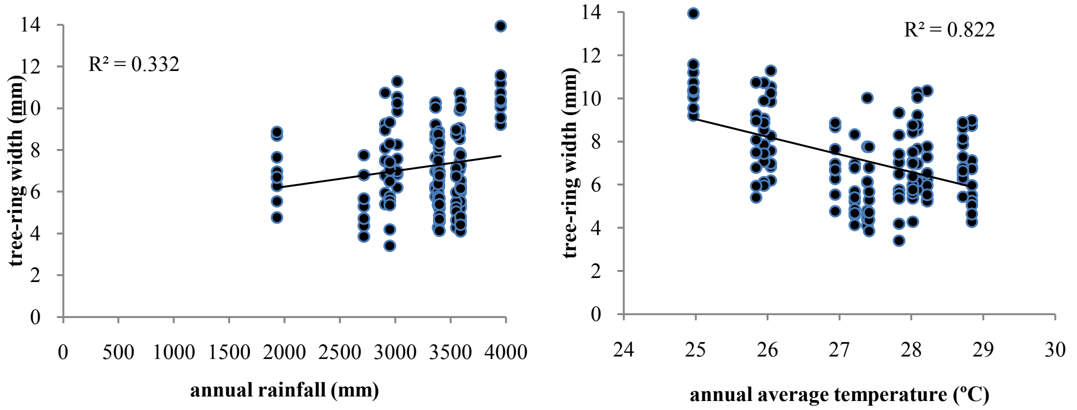


Figure S.7. Individual and mean cumulative diameter increment of teak trees from the investigated stands of 10 years age class plantation in Paukkaung



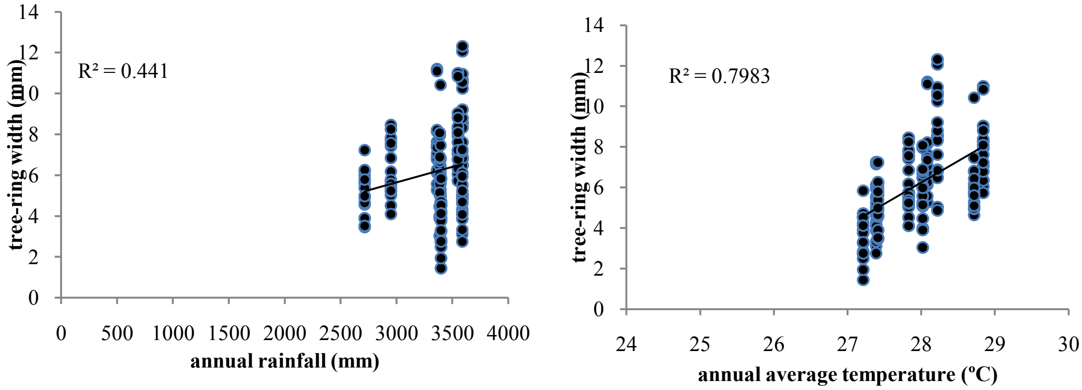
(a) (b)

Figure S.8. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 20 years age class plantation in Bago



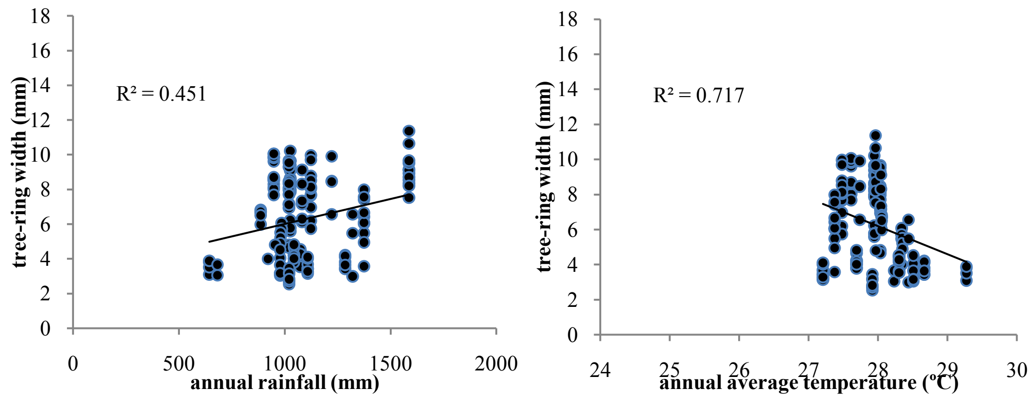
(a) (b)

Figure S.9. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 15 years age class plantation in Bago



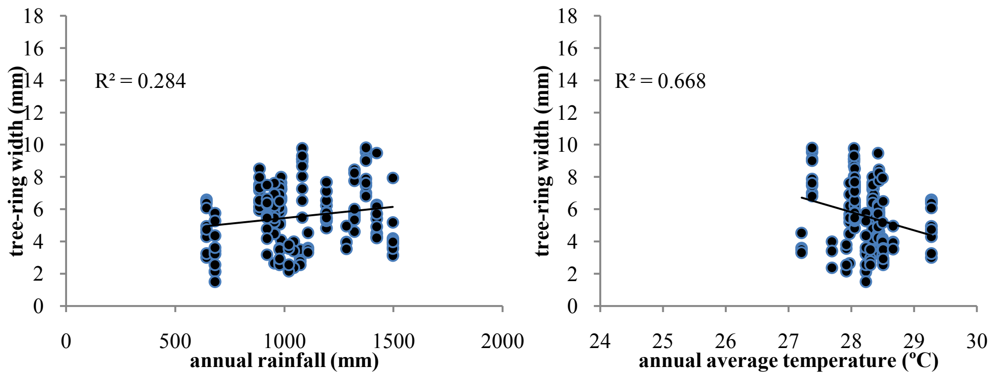
(a) (b)

Figure S.10. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 10 years age class plantation in Bago



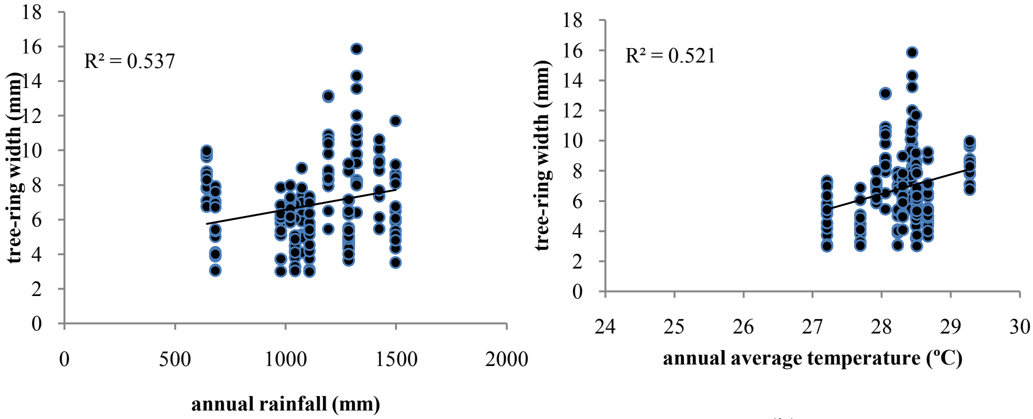
(a) (b)

Figure S.11. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 25 years age class plantation in Paukkaung



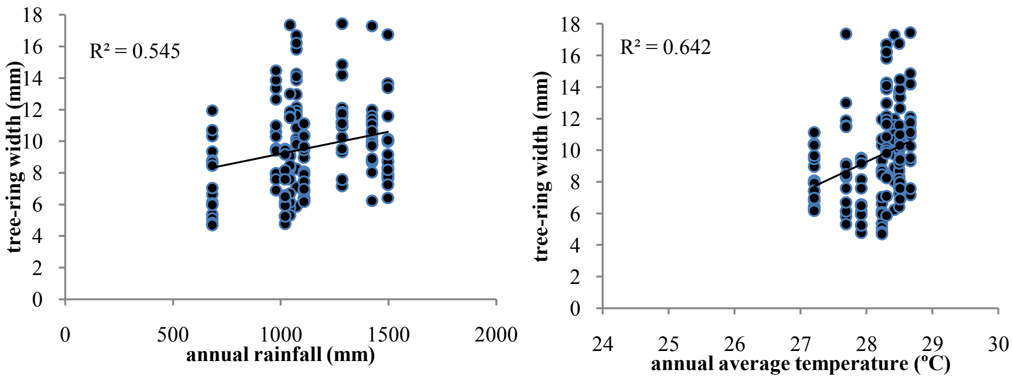
(a) (b)

Figure S.12. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 20 years age class plantation in Paukkaung



(a) (b)

Figure S.13. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 15 years age class plantation in Paukkaung



(a) (b)

Figure S.14. Scatter plots of tree-ring width (mm) and (a) annual rainfall (mm) and (b) annual average temperature (ºC) of 10 years age class plantation in Paukkaung

Table S.1. Soil properties in Bago site

		20 years	15 years	10 years
pH		6.3(0.08)	6.0(0.19)	6.1(0.25)
Total Nitrogen	mg/100g	54.88(7.34)	61.88(6.93)	77.68(8.98)
Ava Phosphorous	mg/100g	0.08(0.04)	0.28(0.17)	0.44(0.32)
Potassium	mg/100g	4.09(0.57)	4.31(0.97)	5.44(0.97)
Calcium	mg/100g	95(7.61)	169(47.94)	181(52.45)
Organic Matter	%	1.80(0.19)	3.47(0.44)	4.07(0.51)
Particle size distribution	Sand%	73(2.95)	68(4.38)	61(9.53)
	Silt %	16(1.51)	18(1.42)	19(2.70)
	Clay %	13(1.79)	12(1.54)	20(2.49)

Numbers are the means with standard derivation in the parentheses

Table S.2. Soil properties in Paukkaung site

		25years	20years	15years	10years
pH		6.0(0.18)	6.0(0.36)	6.1(0.37)	6.2(0.29)
Total Nitrogen	mg/100g	52.46(8.75)	49.96(7.75)	43.55(6.94)	40.54(10.27)
Ava Phosphorous	mg/100g	0.25(0.31)	0.19(0.16)	0.46(0.36)	1.19(0.94)
Potassium	mg/100g	5.42(0.88)	4.53(1.18)	4.41(0.91)	4.15(1.14)
Calcium	mg/100g	240(40.17)	282(47.04)	255(53.02)	297(49.79)
Organic Matter	%	3.73(0.55)	3.29(0.73)	3.08(0.71)	2.80(0.48)
Particle size distribution	Sand%	62(6.50)	68(6.02)	69(6.40)	72(4.95)
	Silt%	22(5.01)	19(2.42)	18(2.57)	16(3.72)
	Clay%	14(3.47)	11(1.58)	12(2.73)	11(2.00)

Numbers are the means with standard derivation in the parentheses

Table S.3. Frequency of trees at stand diameter distribution of study plantations in Bago

Diameter class	10 yrs	15 yrs	20 yrs
5.1-10.0	279	55	
10.1-15.0	189	262	31
15.1-20.0	28	179	98
20.1-25.0		27	99
25.1-30.0			37
30.1-35.0			15

Table S.4. Frequency of trees at stand diameter distribution of study plantations in Paukkaung

Diameter class	10 yrs	15 yrs	20 yrs	25 yrs
5.1-10.0	87	75		
10.1-15.0	296	250	32	
15.1-20.0	172	167	130	17
20.1-25.0	16	13	115	46
25.1-30.0			21	50
30.1-35.0			9	20
35.1-40.0				3

Table S.5. Growth performance of teak plantations

Age	Current stocking	Ave. DBH	Ave. Ht	total Basal Area	total Volume	Increment volume (m3 /ha/ yr)		Site index**
(yrs)	(tree/ha)	(cm)	(m)	(m^2)	(m^3)	MAI	CAI	
5	3000	2	3.3	1.04	-	-	-	40
10	1616	7	7.9	6.56	-	-	-	40
15	746	12	11.7	8.86	8.6	1.0	2.9	40
20	472	17	14.8	10.58	23.1	1.9	4.6	40
25	347	21	17.3	11.96	40.7	2.6	5.5	40

Source: growth and yield tables for plantation teak in Myanmar, Tint *et al.*, 1993

Table S.6. Initial spacing and stand density of study age classes of teak plantations in Bago and Paukkaung

Site	Age class (yrs)	Year	Ave DBH (cm)	Ave Ht (m)	Spacing (m x m)	Initial stands	Current stands	Frequency of Thinning	Site Index
Bago	10 yrs	2001-2010	10.02	9.46	2.7 x 2.7	1329	496	1	40
	15 yrs	1995-2010	14.13	13.70	2.7 x 2.7	1329	523	1	40
	20 yrs	1990-2010	20.58	15.21	2.5 x 2.5	1556	280	2	40
Pauk-kaung	10 yrs	2000-2010	13.71	12.00	2.7 x 2.7	1329	571	1	40
	15 yrs	1998-2010	15.2	14.32	2.7 x 2.7	1329	505	1	40
	20 yrs	1990-2010	21.5	14.93	2.5 x 2.5	1556	307	3	40
	25 yrs	1985-2010	24.88	20.34	2.5 x 2.5	1556	136	4	40

Table S.7. Stand diameter-height relation functions and coefficient parameters estimations for Bago site plantations

Age class (yrs)	Function	Coefficients a	b	RS	r	R^2	
10 yrs	y=1.3+a*exp(b/x)	7.79	-0.02	0.00	0.58	0.34	Michailoff, 1943
	y=a*exp(-b x)	10.05	0.31	19.05	0.55	0.30	Meyer, 1940
	y=a*exp(b x)	7.67	0.02	0.24	0.61	0.37	Exp. fit
15 yrs	y=1.3+a*exp(b/x)	8.96	-0.03	0.00	0.64	0.41	Michailoff, 1943
	y=a*exp(-b x)	16.98	0.11	29.04	0.65	0.72	Meyer, 1940
	y=a*exp(b x)	8.94	0.03	2.04	0.64	0.41	Exp. fit
20 yrs	y=1.3+a*exp(b/x)	10.89	-0.02	0.00	0.66	0.44	Michailoff, 1943
	y=a*exp(-b x)	20.93	0.07	27.27	0.67	0.45	Meyer, 1940
	y=a*exp(b x)	10.39	0.02	3.32	0.70	0.49	Exp. fit

Y = height, x = DBH, a & b = coefficients of the function, RS = standard residual , r = correlation coefficient, R^2 = coefficient of determination

Table S.8. Stand diameter-height relation functions and coefficient parameters estimations for Paukkaung site plantations

Age class (yrs)	Function	Coefficients					
		A	b	RS	r	R^2	
10 yrs	y=1.3+a*exp(b/x)	8.74	-0.02	0.00	0.59	0.34	Michailoff, 1943
	y=a*exp(-b x)	13.84	0.16	31.67	0.56	0.31	Meyer, 1940
	y=a*exp(b x)	8.76	0.02	0.87	0.60	0.36	Exp. fit
15 yrs	y=1.3+a*exp(b/x)	0.64	-0.03	0.00	0.69	0.48	Michailoff, 1943
	y=a*exp(-b x)	15.97	0.13	32.25	0.68	0.46	Meyer, 1940
	y=a*exp(b x)	8.76	0.03	1.63	0.69	0.48	Exp. fit
20 yrs	y=1.3+a*exp(b/x)	8.29	-0.02	0.00	0.72	0.52	Michailoff, 1943
	y=a*exp(-b x)	19.20	0.06	11.22	0.77	0.59	Meyer, 1940
	y=a*exp(b x)	8.16	0.03	2.55	0.75	0.56	Exp. Fit
25 yrs	y=1.3+a*exp(b/x)	8.22	-0.04	0.00	0.87	0.75	Michailoff, 1943
	y=a*exp(-b x)	56.89	0.02	4.29	0.89	0.79	Meyer, 1940
	y=a*exp(b x)	9.05	0.03	13.47	0.85	0.72	Exp. Fit

Y = height, x = DBH, a & b = coefficients of the function, RS = standard residual, r = correlation coefficient, R^2 = coefficient of determination

Table S.9. Stand growth functions and coefficient parameters estimations for Bago site plantations

Function	Parameter	Coefficients a	b	c	d	RS	r	R^2
y=a/(1+exp(bc*x))^1/d (Richard, 1981) a (asymptote) b (growth-rate constant) c, d (coefficients)	DBH	146.81	1.00	0.03	3.65	0.05	0.76	0.58
	Ht	21.54	1.00	0.13	1.05	0.09	0.84	0.71
	Basal Area	262.20	5.86	0.11	0.81	0.00	0.73	0.53
	Volume	102.91	3.249	0.16	0.63	0.02	0.70	0.50
y=a*exp(-exp(b-c*x)) (Gompertz, 1825)	DBH	143.16	1.25	0.03		5.82	0.75	0.56
	Ht	23.09	0.63	0.08		0.46	0.84	0.71
	Basal Area	62.02	2.09	0.10		97.00	0.72	0.52
	Volume	1221.01	1.25	0.02		95.64	0.70	0.49
y=a/(1+b*exp(-c*x)) (Logistic)	DBH	-4.64	-1.69	0.02		19.19	0.76	0.58
	Ht	20.62	3.82	0.13		0.30	0.84	0.71
	Basal Area	-3.85	-2.76	0.04		45.21	0.73	0.53
	Volume	-168.70	-78.08	0.15		1055.73	0.70	0.49

DBH=diameter breast height, Ht = top height, BA = basal area, Vol = volume, RS=standard residual, r = correlation coefficient, R^2 = coefficient of determination, y = parameters, x = time (age)

Table S.10. Stand growth functions and coefficient parameters estimations for Paukkaung site plantations

Function	Parameter	Coefficients a	b	c	d	RS	r	R2
y=a/(1+exp(b-c*x))^1/d (Richard, 1981) a (asymptote) b (growth-rate constant) c,d (coefficients)	DBH	81.21	1.00	0.15	3.37	1.96	0.69	0.48
	Ht	14.29	1.00	0.23	0.93	0.06	0.60	0.36
	Basal Area	307.80	5.23	0.03	0.30	0.45	0.71	0.50
	Volume	245.05	3.62	0.13	0.52	2.71	0.72	0.52
y=a*exp(-exp(b-c*x)) (Gompertz, 1825)	DBH	908.16	1.55	0.01		4.83	0.69	0.48
	Ht	73.68	0.75	0.02		0.19	0.59	0.35
	Basal Area	78.60	0.82	0.02		0.99	0.71	0.50
	Volume	986.31	1.21	0.02		101.80	0.71	0.50
y=a/(1+b*exp(-c*x)) (Logistic)	DBH	-6.69	-1.69	0.01		15.20	0.70	0.49
	Ht	-8.78	-1.93	0.01		2.21	0.61	0.37
	Basal Area	-4.85	-1.93	0.02		132.46	0.72	0.52
	Volume	-3.18	-1.36	0.01		2692.37	0.75	0.56

DBH=diameter breast height, Ht = top height, BA = basal area, Vol = volume, RS=standard residual, r = correlation coefficient, R^2 = coefficient of determination, y = parameters, x = time (age)

ABSTRACT IN KOREAN

미얀마의 천연 티크 (*Tectona grandis* Linn.f) 숲의 면적이 줄어듦에 따라, 현존하는 티크 숲의 생태적 가치를 훼손하지 않고, 천연 티크의 재적을 늘리기 위해 티크 조림지가 오래 전부터 조성되어 왔으며, 이러한 상업적 티크 조림지의 생장량, 생산 잠재력, 사회적 그리고 환경적 영향 등에 대한 조림 성과를 이해하기 위한 평가가 필요하다. 따라서 본 연구의 목적은 상업적 조림지의 성장 유형에 대한 정보를 제공함으로써, 임업인, 산림 경영자 혹은 의사 결정자로 하여금 미얀마 조림 산업에 대해 검토를 가능하게 하고 검토 후, 경영 전략의 적절한 수정을 내리는데 도움이 되고자 한다.

본 연구에서는 상업적 티크 조림지의 조성과 경영에 대한 정보를 제공하기 위해 동부 바고요마의 바고 지역과 서부 바고요마의 파카웅 지역에 위치한 두 티크 조림지의 생장량을 조사하였다. 동부 바고요마의 바고 지역에서는 세 영급의 숲을, 그리고 서부 바고요마의 파카웅 지역에서는 네 영급의 숲을 조사하였으며, 각 실험지에서 1.0 ha 의 실험구를 만들고, 각 실험구에 존재하는 모든 나무의 직경과 수고를 측정하고, 그 중 약 20 개의

나무를 무작위로 선발하여, 성장추를 뚫어 직경생장을 측정하였다. 조사 결과, 연평균 흉고직경 생장량은 바고지역의 경우 1.23 cm 였으며, 파카웅 지역의 경우 평균적으로 연간 1.40 cm 생장하였다. 총평균생산량(MAI)의 경우 바고지역과 파카웅지역이 각각 3.7 $m^3\ ha^{-1}\ yr^{-1}$ 과 4.8 $m^3\ ha^{-1}\ yr^{-1}$ 이었다. 바고지역에서 10, 15, 20 년 된 임분의 흉고 단면적은 각각 5.31, 7.84, 12.00 $m^2\ ha^{-1}$ 이었으며 지경 5cm 이상의 개체수는 496, 523, 280 본 이었다. 파카웅지역에서는 10, 15, 20, 25 년 된 임분에 흉고 단면적은 각각 11.16, 9.54, 11.83, 7.21 $m^2\ ha^{-1}$ 이었으며 지경 5cm 이상의 개체수는 571, 505, 307, 136 본 이었다. 본 실험지에 가장 적합한 생장식은 4 차원 함수였다. 그러나 만약 수집된 자료가 영구 조사지에서 연속적으로 측정된 것이라면, 직경과 수고간 관계 곡선을 도출하기 위한 Michailoff (1943) 함수와 생장 분석을 위한 Richards (1981) 함수가 생장 및 수확표 도출에 있었을 것이다. 본 연구 결과, 바고지역과 파카웅지역 모두 티크 조림지로서 적합한 생태적 조건, 즉 기후, 토양, 지형 등을 가지고 있음을 알 수 있다. 더욱이, 두 지역의 지위지수는 둘

다 40 으로 나타났으나, 바고 지역에 비해 파카웅 지역이 수고 생장을 제외한 직경, 흉고 단면적, 재적 면에서 더 우세한 생장을 나타냈다.

본 연구 결과는 두 실험지 모두 티크 조림지 조성에 적절한, 기후, 토양, 지형을 갖추고 있는 것으로 나타났으며, 본 연구결과가 임업인, 산림 경영자 및 의사결정자에게 티크 조림지의 현황 정보를 제공함으로써, 미얀마 조림사업 성과를 점검하고, 미얀마의 티크 연륜연대학과의 학제간 연계성을 제공할 것으로 기대된다. 또한 임분단위의 직경-수고 간의 관계를 규명할 것과 지역 단위로 상업적 조림지의 생산성을 조사할 것으로 제안한다.

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